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NASA
Technical
Paper
3268

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Technical
Report
92-B-014

February 1993

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(NASA-TP-3268) TRADE-OFFS ARISING FROM MIXTURE OF COLOR CUEING AND MONOCULAR, BINOPTIC, AND STEREOSCOPIC CUEING INFORMATION FOR SIMULATED ROTORCRAFT FLIGHT (NASA) 81 p

N93-18333

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H1/05 0145551

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# Trade-Offs Arising From Mixture of Color Cueing and Monocular, Binoptic, and Stereoscopic Cueing Information for Simulated Rotorcraft Flight

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## Summary

The use of monochrome helmet-mounted display (HMD) systems is becoming prevalent in today's complex flight mission environment. These HMD systems can provide stereoscopic (true depth) cueing as an almost natural by-product for binocular helmet systems if an additional image generation source is provided. The addition of color cueing capability is much more difficult. The application of stereoscopic cueing to advanced HMD and head-down flight display concepts has increased pilot situation awareness and improved task performance. To provide stereopsis, some of the total field of view available with binocular HMD systems must be sacrificed from the two monocular fields to obtain a partial overlap region. The visual field then provides a mixture of cues, with monocular regions on both peripheries and a binoptic (the same image in both eyes) region or, if lateral disparity is introduced to produce two images, a stereoscopic region in the overlapped center.

This paper reports an in-simulator assessment of the trade-offs arising from the mixture of color cueing and monocular, binoptic, and stereoscopic cueing information in peripheral monitoring displays as encountered in HMD systems. The accompanying effect of stereoscopic cueing in the tracking information in the central region of the display was also assessed. Five operationally experienced rotorcraft pilots participated in the study. The pilot's task for the study was to fly at a prescribed height above an undulating pathway in the sky while monitoring a dynamic bar chart displayed in the periphery of their field of view. Control of the simulated rotorcraft was limited to the longitudinal and vertical degrees of freedom to ensure the lateral separation of the viewing conditions of the concurrent tasks.

The results of the experiment indicate that binoptic display of monitoring information in the peripheral region, with color cueing as an alerting function to such information, and stereopscopic cueing in the central region of the display were the most effective display conditions examined, as determined from the objective measures and subjective comments of the pilots.

## 1. Introduction

High-fidelity, "real world" pictorial displays that incorporate true depth (via stereopsis techniques) in the display elements are now available with current electronic display technology. Advanced pictorial flight display concepts that embody 3-D images are being conceived of and evaluated at various flight display research laboratories, including the Langley Research Center. Innovative concepts are being sought that exploit the power of modern graphics display generators and stereoscopic cueing, not only in situational awareness enhancements of pictorial displays but also in displays for the declutter of complex informational displays and in providing more effective alerting functions to the flight crew.

The advantages of the 3-D display of 3-D information, rather than the conventional 2-D display of such information, seem intuitively obvious. These advantages have been investigated for years within the flight display community (refs. 1 to 9). These efforts have been particularly intense for helmet-mounted, head-up display applications, as stereopscopic cueing is an almost natural by-product of binocular helmet systems (refs. 1 to 4). Additional investigations with electronic shutters or polarized filters, rather than helmet optics, used to present separate left- and right-eye views have also been conducted (refs. 4 to 9). Most of these investigations have reported favorable subjective opinions concerning the value of sterescopic cueing, and when objective data were obtained, they generally demonstrated modest task performance gains, or at least no degradations, compared with performance with nonstereo displays. Reference 9 reported a much larger performance gain for stereoscopic cueing, and reference 10 used the desire to include stereoscopic cueing in a helmet-mounted display (HMD) system design to justify a choice between major design alternatives. The use of stereopsis as an alerting function in monitoring task displays has also been investigated. (Ref. 11 found stereopsis to be an ineffective replacement for color cueing.)

To provide stereopsis, binocular HMD systems must trade some of the total field of view (FOV) available from their two monocular fields to obtain a partial overlap region. The visual field then provides a mixture of cues, with monocular regions on both peripheries and a binoptic (the same image in both eyes) region or, if lateral disparity is introduced to produce two images, a stereo region in the overlapped center. With a total overlap, binoptic cueing or stereo cueing can be provided within the entire reduced FOV. The consequences of any of these mixtures have not been thoroughly investigated.

As with the use of stereoscopic cueing, the advantages of using color in information displays seem intuitively obvious and yet its inclusion has sometimes been debated because of the additional costs. The advantages of color have also been investigated for years within the display community (ref. 12).

Unlike stereopsis, color is not available with today's HMD flight systems. The technology does not presently exist to provide color with suitable resolution, brightness, at-eye luminance, and other properties (while maintaining the desired levels of external visibility), although efforts to develop the capability are being pursued (ref. 13).

The goal of this research was to assess the tradeoffs arising from the mixture of color cueing and monocular, binoptic, and stereoscopic cueing information in primary flying and secondary monitoring tasks as encountered in HMD systems. The pilot's task for the study was to fly at a prescribed height above an undulating pathway in the sky while monitoring a dynamic bar chart displayed in the periphery of their FOV. Control of the simulated rotorcraft was limited to the longitudinal and vertical degrees of freedom to ensure the lateral separation of the viewing conditions of the concurrent tasks.

## 2. Experimental Tasks and Participating Pilots

A rotorcraft single-axis vertical tracking task that used a pathway-in-the-sky format was chosen as the primary task for the experiment. A secondary monitoring task (detection and acknowledgment of boundary excursions) was presented in the periphery of the display. (See fig. 1(a).) Since current HMD systems cannot provide the interchangeable conditions of monocular, binoptic, and stereoscopic cueing with color capability, a head-up color stereo monitor configuration was used to present the visual display. Thus, a color, stereo-capable HMD was emulated. The total 40° field of view was partitioned into a 20° central area and 10° left and right peripheral areas (fig. 1(a)). The primary tracking task was presented binocularly as either a nonstereo or a stereo pathway in the central area. Stereopsis in the central area was introduced by means of lateral disparity offsets. The secondary monitoring task was presented in one of the peripheral areas, with either monocular, binoptic, or stereoscopic cueing and with the presence (a blue bar turned red whenever it exceeded the excursion boundary) or absence (no color change) of color cueing.

Five active duty and operationally experienced U.S. Army rotorcraft pilots participated in this study. Each pilot had had extensive experience in rotorcraft of various types. The pilots endeavored to fly 12 ft above the pathway, which undulated in altitude, while monitoring the peripheral display. The pathway display (center of fig. 1(b)) contained the pathway, representations of the sky and ground, a ground grid, a pitch attitude symbol, an instantaneous-flight-pathway-angle indicator, and an altitude-error indicator. The peripheral display consisted of three vertical blue bars that varied continually in amplitude. The pilot's monitoring task was to detect any boundary excursions by any of the three bars and to acknowledge that detection by pressing a button on the cyclic hand controller. With color cueing present, whenever a blue bar exceeded the boundary it turned red. The red bar remained above the boundary for 2 sec. With color cueing absent, the bar remained above the boundary for 2 sec, but it did not change color.

Control of the rotorcraft was limited to the longitudinal and vertical degrees of freedom. The pilot could make inputs with the cyclic hand controller and the collective stick (see fig. 2), but the control was limited within the math model to pitch and altitude effects. Speed was held constant within the math model at 180 knots to ensure experimental control of the variance within the monitoring task. Boundary excursions within the monitoring task were programmed to either occur or not occur within 10 particular regions of the flight pathway, with some random variation of the point of occurrence within those regions. The occurrences were chosen randomly without replacement such that there were a total of eight excursions during a trial or run. A run lasted 90 sec. The assignment of an excursion to a particular bar of the three in the monitoring display was also made randomly.

No lateral movement of the simulated rotorcraft was permitted to ensure the tracking and monitoring tasks remained separated. Intrusion of the pathway into the peripheral areas of the display would additionally violate the separation of monocular and binocular viewing regions. Again, this intrusion was precluded by not allowing lateral movement of the rotorcraft and the pathway.

## 3. Performance Metrics and Experimental Design

The performance metrics for the primary tracking task of the study included root-mean-square (rms) values of the pilot control inputs of cyclic pitch and collective about trim conditions (expected mean values of zero) and the mean, the standard deviation, and the rms of the pathway error during a run. Although there is redundancy within the three measures of pathway error, all three measures were collected and analyzed. The mean altitude tracking error about the desired 12 ft above the pathway-in-the-sky position was of interest because of the solid nature of the pathway. It was anticipated that the pilots would tend to fly higher above the pathway than desired, rather than risk possible penetration of the solid pathway image. The precision of the tracking performance, as indicated by the standard deviation measure, was also collected for pathway-in-the-sky format design interests. However, the rms measure, which includes both the mean effect and the standard deviation effect for nonzero expected mean values, is the traditional tracking performance measure, and so it was also collected and analyzed.

Measures for the monitoring task during a run included the percentage of correct boundary excursions detected and acknowledged, the number of extraneous (false) boundary excursions detected and acknowledged, and the average time to detect and acknowledge an actual (true) excursion. The measure of average time to acknowledge was not affected by a true excursion occurring without being acknowledged by the pilot.

The main factors of interest in the experiment were the display conditions for both the tracking task and the monitoring task. The display conditions examined for the tracking task included the binocular presentation of everything in the 20° central area (the pathway; the sky, ground, and ground grid; and the control symbology) in nonstereo and stereo. The nonstereo display used no depth cues other than those provided by a perspective, real-world display, such as size, shape, interposition, and motion parallax. The display conditions examined for the monitoring task presented everything in the 10° peripheral areas (the sky, ground, and ground grid and the monitoring display) in monocular (one-eye only), binoptic (both eyes), or stereo (both eyes with lateral disparity) conditions. Lateral disparity cues were varied in the stereo condition to cause the monitoring display to modulate in depth as a single unit. The monitoring display unit consisted of the three bars, the boundary line, and the enclosing box. The display unit modulated in depth from the screen out toward the pilot, with the depth varying with the maximum of the amplitudes of the three bars.

Another factor in the experimental design was the presence or absence of color cueing in the display for the monitoring task. Color was used throughout the real-world pictorial display for both the central area and the peripheral areas. However, performance gains, rather than merely the desire for "realism," are often required to justify the inclusion of color in flight displays. In addition to addressing the color issue, examination of the possible performance gains from use of color cueing in the monitoring task would also provide a comparison level for the performance gains realized with the various display conditions.

With the partitioning of the available display area into a central and two peripheral areas, it was possible to examine the effects of the left- or right-side location of the secondary monitoring display. Reference 14 states that "the nerve fibers from the left halves of the retinas (concerned with the right half of the visual field) proceed to the left side of the brain, and the nerve fibers from the right halves of the retinas (concerned with the left half of the visual field) proceed to the right side of the brain." Therefore location of the monitoring task on one side of the display in the monocular, the binoptic, or the stereo condition would result in stimulation of only one side of the brain (ignoring cross talk). Since the two sides of the brain do different tasks with different precision (ref. 15), location of the monitoring task was made another factor of the experiment.

Training was initiated at a low airspeed (110 knots) to enable quick proficiency with all experimental conditions. Training then progressed through each condition at the higher data-collection airspeed (180 knots). The rms pathway-error score (altitude error) was reported to the pilot following each trial. Each pilot achieved approximately asymptotic performance for each of the experimental conditions before data collection was begun. Two replicates of each condition were obtained from each of the five pilots. Both training runs and data-collection runs were blocked across the experimental conditions and balanced across the pilots to negate any possible learning curve effects that might occur after the apparent asymptotic performance was achieved. The order of the experimental conditions flown by each pilot is presented in table 1.

## 4. Simulator Description

The simulator was assembled with the following elements: mathematical model, computer implementation, stereo visual system hardware, graphics generation hardware and software, and simulator cockpit.

### 4.1. Mathematical Model

A simplified two-degree-of-freedom mathematical model of a rotorcraft was used in the study. Figure 3 presents a block diagram of the model. The transfer functions and gains were obtained from reference 16 to represent a highly maneuverable light helicopter.

The undulating pathway was generated with altitude variations from the sum of three sine waves.

The sine waves had normalized amplitudes of 0.4, 0.3, and 0.2, with frequencies of 0.10, 0.25, and 0.40 Hz, respectively.

The three bars of the monitoring task were driven from three different sums of three sine waves with normalized amplitudes of 0.4, 0.3, and 0.2 and frequencies of 0.30, 1.00, and 1.25 Hz, respectively. The phase angles of the three sine waves were randomized at the beginning of each run over a range of $\pm 90^\circ$. The left bar used amplitudes of 0.4, 0.3, and 0.2 in its sum; the middle bar used 0.4, $-0.3$, and 0.2 in its sum; and the right bar used 0.4, $-0.3$, and $-0.2$ in its sum. An excursion was created by changing the amplitude of the 0.30-Hz sine wave for the selected bar from 0.4 to 1.0. The change was gradually fared over a period of 1.5 sec. The bar remained above the boundary for 2.0 sec, and then the amplitude was fared back from 1.0 to 0.4 over a period of 1.5 sec.

### 4.2. Computer Implementation

The mathematical model of the rotorcraft and the simulation hardware drives were implemented on a VAX 11/780 computer in the Langley Crew Station Systems Research Laboratory (ref. 17). This computer system solved the programmed equations 20 times a second. The average time delay from input to output (1.5 times the sample period) was approximately 75 msec.

### 4.3. Stereo Visual System Hardware

The stereo visual system hardware operated on the video signals supplied by the graphics generation system at a resolution of 1280 pixels (horizontally) by 1024 pixels (vertically). These video signals presented a noninterlaced frame at a 60-Hz refresh rate; the frame consisted of both the left-eye and the right-eye stereo-pair image. (See fig. 4.) The stereo visual system hardware (fig. 5) separated the left- and right-eye scenes and presented each alternately, at a 120-Hz refresh rate, spread across the entire monitor screen (i.e., time-multiplexed stereo, which resulted in a loss in vertical resolution of approximately 50 percent), as shown in figures 1 and 4. Liquid crystal device (LCD) glasses were shuttered in synchronization with the stereo pair, such that the right eye saw only the right-eye scene and the left eye saw only the left-eye scene, each at 60 Hz, without flicker. The stereo visual system hardware is described in reference 18.

### 4.4. Graphics Generation Hardware and Software

The graphics generation software resided within a Silicon Graphics IRIS 40/70 GT computer and consisted of the necessary transformation equations and the graphics data bases for the displays. The graphics displays were produced at an update rate of 20 Hz. With an additional time delay of 50 msec added to the image rendering time of 16 msec and the average computational delay of 75 msec, the average time delay for control input to visual output totalled 142 msec.

Figure 6 illustrates the geometric principle that was employed to produce the left- and right-eye views within the stereo-pair generation software. The oblong rectangular shape represents the screen of the display monitor. To present an object that appeared at the depth of the screen, the object was drawn in the same location for both stereo-pair views. For objects to appear behind the screen, the object was displaced to the left of the nominal screen position for the left-eye view and to the right for the right-eye view (with the displacement reaching a maximum value to place an object at infinity). For objects to appear in front of the screen, a displacement to the right was used for the left-eye view and to the left for the right-eye view.

To generate this lateral displacement, which is known as lateral disparity, left- and right-eye coordinate systems were transformed from the viewer coordinate system of the visual scene. The nonstereo condition used a lateral disparity of zero (the vertical display resolution was identical to the stereo condition and the pilots wore the stereo goggles for all conditions), and the stereo condition used disparities resulting from the stereo-pair transformations. The asymmetric clipping algorithm of reference 19 was transposed and then employed to limit each eye view to the viewing volume necessary to generate the desired monocular, binoptic, and stereo regions in the periphery.

Simple perspective division (chapter 6 of ref. 20) was used to transform the 3-D viewing volumes to 2-D viewports, whose centers were offset from the center of the display screen by half of the maximum allowed lateral disparity (i.e., that used to represent objects at infinite distance). Figure 7 illustrates the mapping of a real-world scene to the stereo viewing volume.

Conventional asymptotic transformations, which are used to map the visual scene into the stereo viewing volume, allow the display designer to fix a specific scene distance at the screen location in the viewing volume. (See fig. 8.) Additional control within the transformation allows some shaping of the asymptotic curve. Figure 9 represents the mapping of the visual scene to the stereo 3-D viewing volumes for the stereo display condition. For this experiment, scene infinity was presented 28 in. from the viewer, with the screen distance of 19 in. representing a scene distance of 40 ft.

### 4.5. Simulator Cockpit

A general-purpose pilot workstation configured as a rotorcraft cockpit was used for this study. (See fig. 2.) The cyclic hand controller is spring centered, and the collective stick is a counterbalanced, friction-controlled stick that is representative of a rotorcraft collective stick. No head-down instrumentation other than the display monitor was utilized. The 19 in. monitor was mounted approximately 19 in. from the pilot's eye position to yield a total instantaneous field of view of 40°.

## 5. Experimental Results and Discussion

The investigation was designed as a full-factorial, within-subjects experiment, with pilots $P$, monitoring task display condition $M$, color cueing $C$, tracking task pathway display condition $T$, location of the monitoring task display $L$, and replicates $R$ as the factors. The objective results are presented and discussed first, with the subjective results discussed thereafter.

### 5.1. Analysis of Objective Results

The data collected in the full-factorial experiment were analyzed by means of univariate analyses of variance for each metric. Table 2 is a summary of the results of these analyses for the eight performance measures. A detailed presentation of these analyses can be found in the appendix.

### 5.2. Discussion of Objective Results

Each of the main factors of the experiment is discussed relative to the analyses of the main factors and the interaction terms presented in the appendix for the tracking task performance measures, the tracking task control input measures, and the monitoring task performance measures.

#### *5.2.1. Pilot*

The main effect of pilot variability was highly significant for all performance measures. This result is usually expected in a precision task, and the pilot variability was therefore isolated from the rest of the analyses by its inclusion as a main factor in the experiment.

#### *5.2.2. Monitoring Task Display Condition*

The display condition of the monitoring task symbology (monocular, binoptic, or stereo) affected only the performance of the monitoring task. There were significantly fewer boundary excursions that were detected and acknowledged, and the response times were longer, for the monocular condition than for the binocular condition. There were no significant differences of any consequence between results for the binoptic and stereo display conditions. Presenting the monitoring task display to both eyes (either binoptic or stereo) improved correct detection of boundary excursions by 9 percent (see fig. 10) and reduced detection acknowledgment time by 10 percent (see fig. 11) over results for the monocular display condition.

The results for monocular versus binocular (binoptic or stereo) display conditions agree with the physiological theory of binocular summation (ref. 21). Binocular summation theory predicts that both detection rate and response time will be better with binocular vision than with monocular vision.

The lack of performance differences between the binoptic and stereo display conditions can be attributed to the dramatic decrease in stereoacuity with horizontal displacement from the visual fixation point (ref. 22). With the pilot fixating on the center of the monitor screen in order to perform the tracking task, the lateral disparity in the display of the monitoring task symbology, located in the periphery of the pilot's field of view, is not detectable.

One may infer from these results that the use of stereopsis as an alerting function in peripherally displayed information is not effective. Unless the stereoscopically presented data are fixated by the viewer, the depth cueing will not be perceived. Therefore, unless the information to be presented in the peripheral area is of such complexity that stereo display enhances its interpretation once the subject fixates on the display (it is accessed by some other effective alerting function), peripheral areas do not require stereo display. However, to obtain the advantages of binocular summation with current binoptic displays in the peripheral areas, an effect that is probably desirable in some HMD applications, a sacrifice in total FOV is required. (Stereopsis in the periphery would require the same sacrifice.) This sacrifice may not be severely limiting, particularly if head or eye tracking and slaving are available. However, the performance gains realized from binoptic or stereo display over monocular display in the periphery require a loss of total FOV that may not be justified for all applications.

*5.2.3. Color Cueing*

Color cueing in the monitoring task display symbology affected the performance of both the tracking task (only for the nonstereo pathway condition) and the monitoring task, but it had no consistent effect on the control input activity for the tracking task.

*5.2.3.1. Tracking task performance.* Color cueing affected the tracking task performance only with the nonstereo pathway condition. For example, with the rms altitude error for the nonstereo pathway condition (see fig. 12), the addition of color cueing to the monitoring task display symbology improved performance by 21.6 percent, and the improvement was consistent across all pilots. For the stereo pathway condition, the improvement was a nonsignificant 3.2 percent, and there was no significant improvement for any of the pilots.

Apparently, with the nonstereo pathway and no color cueing, the tracking task performance was degraded because of the time devoted to the monitoring task. The addition of color cueing was effective in reducing the time required for the monitoring task, and this reduction resulted in increased time available for the tracking task and thus improved tracking performance. With the stereo pathway, the pilots could achieve acceptable tracking performance while devoting more time to monitoring the peripheral display, so that the addition of color cueing had no effect on the tracking task performance.

*5.2.3.2. Monitoring task performance.* Figure 13 illustrates the effect of adding color cueing to the monitoring task display. This addition resulted in 35.6 percent more detections (fig. 13(a)) and an 82.2-percent decrease in extraneous reports (fig. 13(b)). These effects were consistent across all pilots, with only magnitude variations from pilot to pilot. The results were also consistent across the other factors of the experiment, including the pathway condition. The detection acknowledgment time was not affected by the addition of color cueing. (Undetected excursions were not scored within this measure.)

These results indicate that color cueing is very effective as an alerting function in monitoring symbology that is placed in peripheral areas of displays.

*5.2.3.4. Inferences from color cueing results.* Color cueing is very effective as an alerting function in peripheral displays, and use of full color in HMD's across the entire FOV will be desired as pictorial information formats are used in HMD applications. At present, color capability for HMD systems requires significant technology development efforts, which are under way (ref. 13).

*5.2.4. Tracking Task Pathway Display Condition*

The display condition of the tracking task pathway affected the performance of both the tracking task and the monitoring task, but it had no consistent effect on the control input activity for the tracking task.

*5.2.4.1. Tracking task performance.* A stereo pathway resulted in improved tracking performance compared with that obtained with a nonstereo pathway, and the improvement was consistent across all pilots. The improvement achieved was much greater when color cueing was absent in the monitoring task display. For example, for the rms altitude error measure (see fig. 14) pilot performance with the stereo pathway display improved 32.7 percent over that with the nonstereo pathway display when color cueing was absent. When color cueing was present, the improvement was still a significant 16.9 percent. Although a reduction from 12 ft to 10 ft may not seem large, the reduction was in an rms measure, not in a mean measure. Therefore the reduction reflected more than just a scalar measure effect in that the distribution was altered as well.

The presentation of the pathway in stereo apparently gives the pilot more information on the present situation relative to the pathway and also allows better anticipation of the future situation. When color cueing is present in the monitoring task display symbology, more time is available to devote to the tracking task, and so the nonstereo-stereo effect is not as pronounced.

*5.2.4.2. Monitoring task performance.* The only consistent effect that the pathway display condition had on the monitoring task performance was a 7.8-percent slower mean response time in acknowledgment of boundary excursion detections with the stereo pathway display than that with the nonstereo display. This effect was consistent for four of the five pilots. (The effect was not significant for one pilot.) In achieving the better tracking performance with the stereo pathway display, the pilots were either slower in detecting a boundary excursion or delayed their acknowledgment of the detection.

*5.2.4.3. Inferences from tracking task display condition results.* The use of stereopsis in the central area of the display is very effective in increasing pilot situation awareness and improving tracking task performance. Stereopsis is especially effective when color cueing is absent from the monitoring task symbology. Trade-offs in total FOV in order to obtain a central stereo region are less severe than the loss of FOV required to obtain binoptic regions in the peripheral area. However, stereopsis also requires an additional image generation source for advanced HMD systems.

#### 5.2.5. *Location of the Monitoring Task Display*

The location of the monitoring task display affected only the performance of the tracking task. No differences were detected in the performance measures of the monitoring task. Both of these results were unexpected. Some of the functions that have been attributed to the right hemisphere of the brain (which was assumed to be utilized when the left-side location for the monitoring display was used, as described previously) include spatial and recognition skills that involve relational and comparative perceptions (ref. 15). The left hemisphere has been determined to be proficient at logic, reasoning, and counting (as well as at controlling the verbal functions).

The monitoring task had been assumed to be a right-brain function, so a left-side location was expected to produce improvements in the monitoring task performance. None were detected. It might then be expected that the left-side location would have provided equal performance in monitoring, but with less time demands. Therefore, more time would have been available for the tracking task, and the additional time would have improved tracking performance with the left-side location.

Yet, the performance of the tracking task (control of altitude) was degraded when the monitoring display was on the left side. For example, a degradation of 9.0 percent in the rms altitude error was obtained for the left-side location compared with the error for the right-side location (fig. 15).

Moderate performance gains occurred in all the tracking task performance measures with the right-side location of the monitoring display. These gains occurred even though most of the pilots preferred the left-side location for the monitoring task display and the task had been theorized to be a right-brain function.

One inference to be drawn from these results is that the pilots scanned the entire screen and thus involved both brain hemispheres in the monitoring task, rather than mostly fixating on the central region. This inference is not supported by either the subjective comments of the pilots or the detection of a difference between the binoptic and stereo conditions that might be expected with a scanning mode.

An alternate hypothesis is offered that seems more plausible. If one theorizes that tracking tasks are also right-brain functions (i.e., flying is an art), then the left-side location for the monitoring task display would perhaps place an additional burden on the right hemisphere and thus result in a degraded tracking performance.

#### 5.2.6. *Replicates*

The replicate factor was not significant for any of the monitoring task performance measures. This result was expected, as each pilot achieved approximate asymptotic performance before data collection was begun.

### 5.3. Subjective Results

Unstructured pilot comments recorded throughout the experiment indicated that every pilot preferred the stereo pathway display condition and the color cueing monitoring task symbology. They felt that the stereo pathway increased their situational awareness and allowed better anticipation of future requirements, so that the tracking task was much easier to fly than it was with the nonstereo display. The color cueing in the monitoring task display was felt to make boundary excursions obvious, and the pilots were surprised that their detection percentages were not even higher than they proved to be for that condition. Although the pilots could detect the difference between the monocular, the binoptic, and the stereo presentation condition of the monitoring display if they were requested to do so, most of them reported that they were rarely aware of the condition during tracking, and they anticipated no differences in monitoring performance results. One pilot reported that the monocular condition required more concentration than the other two conditions. Most of the pilots preferred the left-side location for the monitoring display, either because that was what they were used to or because they felt that they could see it better there. None of the pilots expected the location to have an effect on performance.

## 6. Concluding Remarks

This paper has assessed the trade-offs arising from the mixture of color cueing and monocular, binoptic, and stereopscopic cueing information in primary flying and secondary monitoring tasks as encountered with helmet-mounted display (HMD) systems. Since current HMD systems cannot provide the interchangeable conditions of monocular, binoptic, and stereopscopic cueing with color capability, a head-up color stereo monitor configuration was used to present the visual display. Thus, a color, stereo-capable HMD was emulated. The main factors of interest in the experiment were the display conditions for both a tracking task and a monitoring task.

The display conditions examined for the tracking task included the binocular presentation of everything in the central area in nonstereo and in stereo. The display conditions examined for the monitoring task presented everything in the peripheral areas in monocular, binoptic, or stereo conditions. Other factors in the experimental design were the presence or absence of color cueing in the display for the monitoring task and the location of the monitoring task display.

Of the display conditions examined, most effective was the use of stereopsis in the central area of the display. Stereopsis was very effective in increasing pilot situational awareness and improved longitudinal tracking task performance. In the subject experiment, stereopsis was especially effective when color cueing was absent from the monitoring task display symbology. The use of stereopsis as an alerting function in peripherally displayed information is not effective. However, there were slight advantages because of binocular summation with binoptic displays in the peripheral areas.

Color cueing in the periphery displays was very effective as an alerting function, and full color in HMD's across the entire FOV will be desirable when pictorial information formats are used in HMD applications. Moderate performance gains occurred with the right-side location of the monitoring task display, even though most of the pilots preferred the left-side location for the monitoring task display, and the task had been theorized to be a right-brain function. Moreover, the performance gains occurred within the tracking task, rather than within the monitoring task.

The results of this experiment indicate that binoptic display of monitoring information in the right peripheral area, with color cueing as an alerting function to such information, and stereoscopic cueing in the central area of the display were the most effective display conditions examined. To obtain the advantages of binocular summation with binoptic displays in the peripheral area, a sacrifice in total field of view (FOV) is required. The performance gains realized from binoptic or stereopscopic cueing over those from monocular cueing in the periphery require a loss of total FOV that may not be justified for all applications. To obtain color cueing in HMD systems, significant technology development efforts are required. In order to realize the advantages of stereoscopic cueing in the central area, an additional image generation source is required for advanced HMD systems.

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November 2, 1992

# 7. Appendix

## Analyses of Variance for Experiment Metrics

The investigation was designed as a full-factorial, within-subjects experiment, with pilots ($P = 1$ to 5), monitoring task display condition ($M$ is monocular, binoptic, or stereo), color cueing ($C$ is absent or present), tracking task pathway display condition ($T$ is nonstereo or stereo), location of the monitoring task display ($L$ is left side or right side), and replicates ($R = 1$ or 2) as the factors. The data collected in the full-factorial experiment were analyzed by means of univariate analyses of variance for each metric. Table 2 is a summary of the results of these analyses for the eight performance measures. The presentation of the results examines each factor within each task, measure by measure. Newman-Keuls testing (ref. 23) of individual means was performed at various stages in the analyses. (All tests were made at a significance level of 1 percent.)

### 7.1. Tracking Task Altitude Errors

Pathway tracking performance was gathered by computing the cumulative mean, standard deviation, and rms of the altitude error over the length of a run.

#### *7.1.1. Pilot*

The main effect of pilot variability was highly significant for all three measures. Figure 16 presents the average mean altitude error for each pilot to demonstrate this effect. A strong variability between pilots is usually expected in a precision task. Contrary to expectations, the mean altitude error results for each pilot indicated that rather than flying higher above the solid pathway, the pilots flew slightly lower than the desired level of 12 ft. Apparently, the solid nature of the pathway did not deter their attempts to fly at the correct relative altitude.

#### *7.1.2. Monitoring Task Display Condition*

This factor was not significant for any of the tracking task measures.

#### *7.1.3. Color Cueing*

This factor was highly significant for all the altitude error measures, with better performance in the tracking task occurring when color cueing was present in the monitoring task display. Figures 17, 18, and 19 present the mean, the standard deviation, and the rms of the altitude error averaged over all the other factors of the experiment. Two second-order interactions involving the color cueing factor were also statistically significant: the interaction of pilot and color cueing ($P \times C$) and the interaction of color cueing and tracking task pathway display condition ($C \times T$).

The significances of the three measures for $P \times C$ indicated that the color cueing effect was not constant across pilots. Figures 20, 21, and 22 show the effect of color cueing on the mean, the standard deviation, and the rms of the altitude error for each pilot. From figure 20, the mean errors of pilots 2, 3, and 4 were better for color cueing absent (although only the difference in the means of pilot 2 was statistically significant), while the mean errors of pilots 1 and 5 were better for color cueing present. (Both differences were significant.) From figure 21, pilots 1, 2, and 5 had some statistically significant improvement in performance for color cueing present versus that for color cueing absent. Pilots 3 and 4 exhibited no statistically significant effect for the color cueing factor. The rms error, which is correlated with both the mean and standard deviation measures, is shown in figure 22, and it improved for color cueing present compared with the error for color cueing absent for all five pilots; however, the degree of improvement was slight (and not statistically significant) for pilots 3 and 4.

The significances of the altitude error measures for $C \times T$ indicated that the color cueing effect was not constant across pathway display conditions. This effect is shown in figure 23 for the mean altitude error. For the nonstereo display of the pathway in the tracking task, color cueing greatly improved performance. For the stereo display of the tracking task, the mean altitude error was essentially unaffected by the presence or absence of color cueing in the monitoring task display. Figure 24 shows the same trend for the standard deviation of the altitude error. However, the third-order interaction of pilot, color cueing, and pathway display condition ($P \times C \times T$) was also significant for this measure (and also for the rms altitude error). Because $P \times C$ was significant while $P \times T$ was not, $P \times C \times T$ is plotted in figures 25 and 26 as $P \times C$ for the respective $T$ conditions of nonstereo and stereo pathway display. As shown in figure 25, the tracking performance of four of the five pilots, using a nonstereo pathway display, improved when color cueing was present in the monitoring task display. (The improvement of pilot 3 was not statistically significant.) Figure 26, however, shows that some pilots' performances improved while others worsened when color cueing was present in the monitoring task display with the stereo pathway display. The amounts of change with the stereo display were less than the amounts of change with the nonstereo display, although none of these changes were statistically significant.

Figure 12 shows that color cueing in the monitor task display greatly reduced the rms altitude error (i.e., improved performance) for the nonstereo display of the pathway in the tracking task. For the stereo display of the tracking task, the rms altitude error was essentially unaffected by the presence or absence of color cueing in the monitoring task display. However, the third-order interaction $P \times C \times T$ was also significant for this measure. Because $P \times C$ was significant while $P \times T$ was not, $P \times C \times T$ is plotted in figures 27 and 28 as $P \times C$ for the respective $T$ conditions of nonstereo and stereo pathway display. Figure 27 shows that the rms tracking performance of each pilot, using a nonstereo pathway display, improved when color cueing was present in the monitoring task display (although the improvement of pilot 3 was not statistically significant). Figure 28, however, shows that some pilots' performances improved while others worsened when color cueing was present in the monitoring task display with the stereo pathway display. The amounts of change with the stereo display were less than the amounts of change with the nonstereo display, although none of these changes were statistically significant.

*7.1.4. Tracking Task Pathway Display Condition*

This factor was highly significant for all the altitude error measures, with better performance in the tracking task occurring when stereo was present in the tracking pathway display than occurred for the nonstereo condition. The second- and third-order interactions involving the pathway display condition and the color cueing condition ($C \times T$ and $P \times C \times T$, which have already been discussed under the color cueing factor) are examined again, this time as $T \times C$ and $P \times T \times C$ for the appropriate measures.

Figure 29 shows the improved performance in mean altitude error for a stereo pathway display compared with that for a nonstereo pathway display. Figure 30 replots the data of figure 23 ($C \times T$), and it shows that the improved performance obtained with a stereo display was greater when color cueing was absent in the monitoring task display than it was when color cueing was present. The improvement in both cases was statistically significant.

Figure 31 shows the reduction in standard deviation of altitude error for a stereo pathway display over that for a nonstereo pathway display. Figure 32 replots the data of figure 24 ($C \times T$), and it shows that the improved performance obtained with a stereo display was greater when color cueing was absent in the monitoring task display than it was when color cueing was present. The improvement in both cases was statistically significant. Figures 33 and 34 replot the data of figures 25 and 26 as $P \times T \times C$, and both figures show that the performance of all pilots, as measured by the standard deviation of altitude error, improved about the same amount with the stereo pathway display. ($P \times T$ was not significant.) The improvement was greater when color cueing was absent from the monitoring task display than it was when color cueing was present, as was indicated by the significance of $T \times C$. Therefore the third-order interaction should be interpreted as $P \times C \times T$ rather than as $P \times T \times C$.

Figures 35, 14, 36, and 37 present the rms altitude error for the situation comparable to that of figures 31, 32, 33, and 34, and the logical analysis is exactly the same. Performance was improved with a stereo pathway display, the performance improvement was larger when color cueing was absent in the monitoring task display than it was when color cueing was present, the improvement in both cases was statistically significant, and the effects were about the same for every pilot.

*7.1.5. Location of the Monitoring Task Display*

This factor was highly significant for all the altitude error measures, with the best performance of the tracking task occurring when the monitoring task display was presented on the right side of the monitor screen. Figures 38, 39, and 15 present the mean, the standard deviation, and the rms of the altitude error averaged over all the other factors of the experiment.

*7.1.6. Replicates*

The replicate factor was not significant for any of the altitude error measures. This result was expected, as each pilot achieved approximate asymptotic performance based on the rms measure for each of the four experimental conditions before data collection was begun.

### 7.2. Tracking Task Control Inputs

Control input activity was recorded as the rms of the pitch and collective stick inputs over the length of a run.

*7.2.1. Pilot*

The main effect of pilot variability was highly significant for both measures. No figures are presented to demonstrate this effect, which is usually encountered in a precision task. Pilot 5 used no collective input for any of the runs, relying solely on pitch control to regulate altitude.

*7.2.2. Monitoring Task Display Condition*

This factor was not significant for any of the control input measures.

*7.2.3. Color Cueing*

This factor was not significant for any of the control input measures. However, the interaction of pilot and color cueing ($P \times C$) was highly significant for collective input activity. Figure 40 demonstrates that pilot 1 exhibited less collective activity when color cueing was present than when color cueing was absent, while pilot 2 exhibited the opposite behavior. Color cueing had no significant effect for pilots 3 and 4.

*7.2.4. Tracking Task Pathway Display Condition*

This factor was highly significant for both control input activity measures. Because of the different combinations of significances of second- and third-order interactions, each of the measures is examined separately.

*7.2.4.1. Pitch input activity.* In addition to the highly significant factor of pathway display condition ($T$), three second-order ($P \times T$, $T \times L$, and $P \times L$) and one third-order ($P \times T \times L$) interaction terms were significant for this measure. Figure 41 shows that the pilots, on average, exhibited more pitch activity for the stereo pathway display than they did for the nonstereo pathway display. However, the significance of $P \times T$ indicated that this fact was not true for individual pilots, as shown in figure 42. Pilot 3 used about the same amount of activity for either display, while pilot 4 used less activity for the stereo display than for the nonstereo display (although the difference was not statistically significant). The significance of $T \times L$ indicated that the effect of the pathway display condition varied with the location of the monitoring task display. Figure 43 illustrates that the pathway display condition affected pitch input activity more for a monitoring task display location on the left side. (The location main factor was not significant for this measure.) More pitch control activity was indicated for the stereo pathway than for the nonstereo pathway when the monitoring task display was located on the left side. Newman-Keuls testing of the means of figure 43 revealed no significant difference between means for the right-side location of the monitoring task display. The third-order interaction $P \times T \times L$ is presented in figures 44 and 45. Newman-Keuls testing of the means of figure 44 revealed no significant differences in the pitch input activity of each pilot for either the stereo or the nonstereo pathway display when the monitoring task display was located on the right side. Testing of the means of figure 45, however, revealed that three of the five pilots used significantly more pitch input activity for the stereo pathway display than for the nonstereo pathway display when the monitoring task display was located on the left side. (Pilots 3 and 4 had no significant differences.)

*7.2.4.2. Collective input activity.* In addition to the highly significant main factor of pathway display condition ($T$), the second-order interaction term with pilots ($P \times T$) was significant for this measure. Figure 46 shows that the pilots, on the average, exhibited more collective activity for the stereo pathway display than for the nonstereo pathway display. However, the significance of $P \times T$ indicated that this was not true for individual pilots, as shown in figure 47. Pilots 1, 3, and 4 exhibited more activity for the stereo pathway display than for the nonstereo pathway display, while pilot 2 used less activity for the stereo than for the nonstereo pathway display. Pilot 5 did not use collective input at all. These differences were statistically significant only for pilots 1 and 4.

*7.2.5. Location of the Monitoring Task Display*

This factor was highly significant for the collective activity measure, with more collective activity being indicated in the tracking task when the monitoring task display was located on the right side of the monitor screen. Figure 48 presents the rms collective input for the two conditions averaged over all the other factors of the experiment. The second-order interaction term $P \times L$ was also statistically significant and, as shown in figure 49, the location of the monitoring task display had an effect on only pilots 2 and 3.

*7.2.6. Replicates*

The replicate factor was not significant for the control input measures. This result was expected, as each pilot achieved approximate asymptotic performance before data collection was begun.

### 7.3. Monitoring Task Performances

Monitoring task performance was determined by computing the percentage of correct boundary excursions detected and acknowledged, the number of extraneous (false) boundary excursions acknowledged, and the average time to acknowledge a true excursion over the length of a run.

#### *7.3.1. Pilot*

The main effect of pilot variability was highly significant for all three measures. No figures are offered to demonstrate this effect, which is usually encountered in a precision task.

#### *7.3.2. Monitoring Task Display Condition*

This factor was highly significant for two of the monitoring task performance measures, detection percentage and detection acknowledgment time. Because of the differences in the involvement of the second-order interaction with pilots, the measures are addressed separately.

Figure 10 presents the average detection percentages achieved with each monitoring task display condition. Significantly fewer detections were acknowledged with the monocular display than with either the binoptic or the stereo display. The difference between the mean detections with the binoptic and the stereo display was not significant. The second-order interaction with the pilot factor ($P \times M$) was also significant for this measure, and figure 50 presents a plot of this interaction. The detection percentage of pilot 3 for the monocular condition was not significantly different from either percentage for the other two conditions, while pilot 4 had equivalent percentages for the monocular and stereo conditions. Pilot 4 had a statistically significant difference in detection percentages for the binoptic and the stereo display condition, while the other four pilots had statistically equivalent percentages for these two conditions.

Figure 11 presents the average excursion detection acknowledgment time achieved with each monitoring task display condition. Significantly more time was required for the detections to be acknowledged with the monocular display than with either the binoptic or the stereo display. The difference between the mean acknowledgment times for the binoptic and the stereo display was not significant. The second-order interaction with the pilot factor ($P \times M$) was not significant for this measure.

#### *7.3.3. Color Cueing*

This factor was highly significant for two of the monitoring performance measures, detection percentage and extraneous detections. These measures are addressed separately.

Figure 51 presents the average detection percentage achieved with and without color cueing in the monitoring task display. Significantly fewer detections were acknowledged with color cueing absent than with color cueing present. The second-order interaction with the pilot factor ($P \times C$) was also significant for this measure, and figure 52 presents a plot of this interaction. As shown, the color cueing effect, while consistent across pilots, was more pronounced for some pilots than for others. (The effect was statistically significant for all pilots.)

Figure 53 presents the average extraneous detections per tracking run with and without color cueing in the monitoring task display. Significantly more extraneous detections were reported with color cueing absent than with color cueing present. The second-order interaction with the pilot factor ($P \times C$) was also significant for this measure, and figure 54 presents a plot of this interaction. As shown, the color cueing effect was more pronounced for some pilots than for others. (The effect was statistically significant for all pilots.)

The interaction of pilot and color cueing was significant for the excursion detection acknowledgment time measure, without the main factor of color cueing being significant. Figure 55 illustrates that two pilots were faster, two were slower, and one had no difference in performance when color cueing was present in the monitoring task display. (The differences were statistically significant only for pilots 3 and 5.) On the average, the color cueing effect was negligible for this measure.

#### *7.3.4. Tracking Task Pathway Display Condition*

This factor was highly significant only for the excursion detection acknowledgment time measure. Figure 56 presents the average detection acknowledgment time for the monitoring task with the nonstereo and the stereo tracking task pathway display. Significantly less time to acknowledge a boundary detection was required for the nonstereo display than for the stereo display. The second-order interaction with the pilot factor ($P \times T$) was also significant for this measure, and figure 57 presents a plot of this interaction. As shown, four pilots took longer to acknowledge a boundary excursion when flying with the stereo pathway display than when flying with the nonstereo pathway display, while pilot 1 took less time to acknowledge an excursion with the stereo display. However, of these differences, only that of pilot 2 was statistically significant.

The interaction of pilot and pathway display condition ($P \times T$) was significant for the detection percentage measure, without the main factor of pathway display condition being significant. Figure 58 illustrates that pilot 2 acknowledged significantly fewer detections when flying with the stereo pathway display than when flying with the nonstereo pathway display; pilot 1 acknowledged significantly more detections under those circumstances, and the other pilots had no statistically significant differences in performance. On the average, the pathway display effect was negligible for this measure.

#### *7.3.5. Location of the Monitoring Task Display*

This factor was not significant for any of the monitoring task performance measures.

#### *7.3.6. Replicates*

The replicate factor was not significant for any of the monitoring task performance measures. This result was expected, as each pilot achieved approximate asymptotic performance before data collection was begun.

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Table 1. Order of Experimental Conditions

| Pilot | Run | Monitor condition | Color cueing | Pathway condition | Location | Replicates |
|---|---|---|---|---|---|---|
| 1 | 1 | Monocular | Absent | Nonstereo | Left | 1 |
| | 2 | Stereo | Absent | Nonstereo | Left | 1 |
| | 3 | Binoptic | Absent | Nonstereo | Left | 1 |
| | 4 | Monocular | Absent | Nonstereo | Left | 2 |
| | 5 | Binoptic | Absent | Nonstereo | Left | 2 |
| | 6 | Stereo | Absent | Nonstereo | Left | 2 |
| | 7 | Binoptic | Absent | Nonstereo | Right | 1 |
| | 8 | Monocular | Absent | Nonstereo | Right | 1 |
| | 9 | Stereo | Absent | Nonstereo | Right | 1 |
| | 10 | Monocular | Absent | Nonstereo | Right | 2 |
| | 11 | Binoptic | Absent | Nonstereo | Right | 2 |
| | 12 | Stereo | Absent | Nonstereo | Right | 2 |
| | 13 | Stereo | Absent | Stereo | Left | 1 |
| | 14 | Binoptic | Absent | Stereo | Left | 1 |
| | 15 | Monocular | Absent | Stereo | Left | 1 |
| | 16 | Binoptic | Absent | Stereo | Left | 2 |
| | 17 | Monocular | Absent | Stereo | Left | 2 |
| | 18 | Stereo | Absent | Stereo | Left | 2 |
| | 19 | Monocular | Absent | Stereo | Right | 1 |
| | 20 | Binoptic | Absent | Stereo | Right | 1 |
| | 21 | Stereo | Absent | Stereo | Right | 1 |
| | 22 | Binoptic | Absent | Stereo | Right | 2 |
| | 23 | Monocular | Absent | Stereo | Right | 2 |
| | 24 | Stereo | Absent | Stereo | Right | 2 |
| | 25 | Stereo | Present | Nonstereo | Left | 1 |
| | 26 | Monocular | Present | Nonstereo | Left | 1 |
| | 27 | Binoptic | Present | Nonstereo | Left | 1 |
| | 28 | Monocular | Present | Nonstereo | Left | 2 |
| | 29 | Stereo | Present | Nonstereo | Left | 2 |
| | 30 | Binoptic | Present | Nonstereo | Left | 2 |
| | 31 | Monocular | Present | Nonstereo | Right | 1 |
| | 32 | Stereo | Present | Nonstereo | Right | 1 |
| | 33 | Binoptic | Present | Nonstereo | Right | 1 |
| | 34 | Monocular | Present | Nonstereo | Right | 2 |
| | 35 | Binoptic | Present | Nonstereo | Right | 2 |
| | 36 | Stereo | Present | Nonstereo | Right | 2 |
| | 37 | Stereo | Present | Stereo | Left | 1 |
| | 38 | Monocular | Present | Stereo | Left | 1 |
| | 39 | Binoptic | Present | Stereo | Left | 1 |
| | 40 | Monocular | Present | Stereo | Left | 2 |
| | 41 | Stereo | Present | Stereo | Left | 2 |
| | 42 | Binoptic | Present | Stereo | Left | 2 |
| | 43 | Binoptic | Present | Stereo | Right | 1 |
| | 44 | Monocular | Present | Stereo | Right | 1 |
| | 45 | Stereo | Present | Stereo | Right | 1 |
| | 46 | Monocular | Present | Stereo | Right | 2 |
| | 47 | Stereo | Present | Stereo | Right | 2 |
| | 48 | Binoptic | Present | Stereo | Right | 2 |

Table 1. Continued

| Pilot | Run | Monitor condition | Color cueing | Pathway condition | Location | Replicates |
|---|---|---|---|---|---|---|
| 2 | 1 | Stereo | Absent | Stereo | Left | 1 |
| | 2 | Monocular | Absent | Stereo | Left | 1 |
| | 3 | Binoptic | Absent | Stereo | Left | 1 |
| | 4 | Monocular | Absent | Stereo | Left | 2 |
| | 5 | Binoptic | Absent | Stereo | Left | 2 |
| | 6 | Stereo | Absent | Stereo | Left | 2 |
| | 7 | Binoptic | Absent | Stereo | Right | 1 |
| | 8 | Monocular | Absent | Stereo | Right | 1 |
| | 9 | Stereo | Absent | Stereo | Right | 1 |
| | 10 | Monocular | Absent | Stereo | Right | 2 |
| | 11 | Binoptic | Absent | Stereo | Right | 2 |
| | 12 | Stereo | Absent | Stereo | Right | 2 |
| | 13 | Monocular | Absent | Nonstereo | Left | 1 |
| | 14 | Stereo | Absent | Nonstereo | Left | 1 |
| | 15 | Binoptic | Absent | Nonstereo | Left | 1 |
| | 16 | Stereo | Absent | Nonstereo | Left | 2 |
| | 17 | Monocular | Absent | Nonstereo | Left | 2 |
| | 18 | Binoptic | Absent | Nonstereo | Left | 2 |
| | 19 | Stereo | Absent | Nonstereo | Right | 1 |
| | 20 | Monocular | Absent | Nonstereo | Right | 1 |
| | 21 | Binoptic | Absent | Nonstereo | Right | 1 |
| | 22 | Monocular | Absent | Nonstereo | Right | 2 |
| | 23 | Stereo | Absent | Nonstereo | Right | 2 |
| | 24 | Binoptic | Absent | Nonstereo | Right | 2 |
| | 25 | Monocular | Present | Stereo | Left | 1 |
| | 26 | Binoptic | Present | Stereo | Left | 1 |
| | 27 | Stereo | Present | Stereo | Left | 1 |
| | 28 | Monocular | Present | Stereo | Left | 2 |
| | 29 | Binoptic | Present | Stereo | Left | 2 |
| | 30 | Stereo | Present | Stereo | Left | 2 |
| | 31 | Binoptic | Present | Stereo | Right | 1 |
| | 32 | Monocular | Present | Stereo | Right | 1 |
| | 33 | Stereo | Present | Stereo | Right | 1 |
| | 34 | Binoptic | Present | Stereo | Right | 2 |
| | 35 | Stereo | Present | Stereo | Right | 2 |
| | 36 | Monocular | Present | Stereo | Right | 2 |
| | 37 | Monocular | Present | Nonstereo | Left | 1 |
| | 38 | Stereo | Present | Nonstereo | Left | 1 |
| | 39 | Binoptic | Present | Nonstereo | Left | 1 |
| | 40 | Stereo | Present | Nonstereo | Left | 2 |
| | 41 | Monocular | Present | Nonstereo | Left | 2 |
| | 42 | Binoptic | Present | Nonstereo | Left | 2 |
| | 43 | Stereo | Present | Nonstereo | Right | 1 |
| | 44 | Binoptic | Present | Nonstereo | Right | 1 |
| | 45 | Monocular | Present | Nonstereo | Right | 1 |
| | 46 | Binoptic | Present | Nonstereo | Right | 2 |
| | 47 | Monocular | Present | Nonstereo | Right | 2 |
| ↓ | 48 | Stereo | Present | Nonstereo | Right | 2 |

Table 1. Continued

| Pilot | Run | Monitor condition | Color cueing | Pathway condition | Location | Replicates |
|---|---|---|---|---|---|---|
| 3 | 1 | Binoptic | Present | Nonstereo | Left | 1 |
| | 2 | Stereo | Present | Nonstereo | Left | 1 |
| | 3 | Monocular | Present | Nonstereo | Left | 1 |
| | 4 | Binoptic | Present | Nonstereo | Left | 2 |
| | 5 | Monocular | Present | Nonstereo | Left | 2 |
| | 6 | Stereo | Present | Nonstereo | Left | 2 |
| | 7 | Stereo | Present | Nonstereo | Right | 1 |
| | 8 | Monocular | Present | Nonstereo | Right | 1 |
| | 9 | Binoptic | Present | Nonstereo | Right | 1 |
| | 10 | Monocular | Present | Nonstereo | Right | 2 |
| | 11 | Stereo | Present | Nonstereo | Right | 2 |
| | 12 | Binoptic | Present | Nonstereo | Right | 2 |
| | 13 | Monocular | Present | Stereo | Left | 1 |
| | 14 | Binoptic | Present | Stereo | Left | 1 |
| | 15 | Stereo | Present | Stereo | Left | 1 |
| | 16 | Binoptic | Present | Stereo | Left | 2 |
| | 17 | Monocular | Present | Stereo | Left | 2 |
| | 18 | Stereo | Present | Stereo | Left | 2 |
| | 19 | Binoptic | Present | Stereo | Right | 1 |
| | 20 | Monocular | Present | Stereo | Right | 1 |
| | 21 | Stereo | Present | Stereo | Right | 1 |
| | 22 | Monocular | Present | Stereo | Right | 2 |
| | 23 | Binoptic | Present | Stereo | Right | 2 |
| | 24 | Stereo | Present | Stereo | Right | 2 |
| | 25 | Stereo | Absent | Nonstereo | Left | 1 |
| | 26 | Monocular | Absent | Nonstereo | Left | 1 |
| | 27 | Binoptic | Absent | Nonstereo | Left | 1 |
| | 28 | Monocular | Absent | Nonstereo | Left | 2 |
| | 29 | Binoptic | Absent | Nonstereo | Left | 2 |
| | 30 | Stereo | Absent | Nonstereo | Left | 2 |
| | 31 | Binoptic | Absent | Nonstereo | Right | 1 |
| | 32 | Stereo | Absent | Nonstereo | Right | 1 |
| | 33 | Monocular | Absent | Nonstereo | Right | 1 |
| | 34 | Binoptic | Absent | Nonstereo | Right | 2 |
| | 35 | Stereo | Absent | Nonstereo | Right | 2 |
| | 36 | Monocular | Absent | Nonstereo | Right | 2 |
| | 37 | Stereo | Absent | Stereo | Left | 1 |
| | 38 | Binoptic | Absent | Stereo | Left | 1 |
| | 39 | Monocular | Absent | Stereo | Left | 1 |
| | 40 | Binoptic | Absent | Stereo | Left | 2 |
| | 41 | Stereo | Absent | Stereo | Left | 2 |
| | 42 | Monocular | Absent | Stereo | Left | 2 |
| | 43 | Binoptic | Absent | Stereo | Right | 1 |
| | 44 | Monocular | Absent | Stereo | Right | 1 |
| | 45 | Stereo | Absent | Stereo | Right | 1 |
| | 46 | Binoptic | Absent | Stereo | Right | 2 |
| | 47 | Stereo | Absent | Stereo | Right | 2 |
| ↓ | 48 | Monocular | Absent | Stereo | Right | 2 |

Table 1. Continued

| Pilot | Run | Monitor condition | Color cueing | Pathway condition | Location | Replicates |
|---|---|---|---|---|---|---|
| 4 | 1 | Binoptic | Absent | Nonstereo | Left | 1 |
| | 2 | Monocular | Absent | Nonstereo | Left | 1 |
| | 3 | Stereo | Absent | Nonstereo | Left | 1 |
| | 4 | Monocular | Absent | Nonstereo | Left | 2 |
| | 5 | Stereo | Absent | Nonstereo | Left | 2 |
| | 6 | Binoptic | Absent | Nonstereo | Left | 2 |
| | 7 | Stereo | Absent | Nonstereo | Right | 1 |
| | 8 | Binoptic | Absent | Nonstereo | Right | 1 |
| | 9 | Monocular | Absent | Nonstereo | Right | 1 |
| | 10 | Binoptic | Absent | Nonstereo | Right | 2 |
| | 11 | Stereo | Absent | Nonstereo | Right | 2 |
| | 12 | Monocular | Absent | Nonstereo | Right | 2 |
| | 13 | Monocular | Present | Nonstereo | Left | 1 |
| | 14 | Stereo | Present | Nonstereo | Left | 1 |
| | 15 | Binoptic | Present | Nonstereo | Left | 1 |
| | 16 | Stereo | Present | Nonstereo | Left | 2 |
| | 17 | Monocular | Present | Nonstereo | Left | 2 |
| | 18 | Binoptic | Present | Nonstereo | Left | 2 |
| | 19 | Binoptic | Present | Nonstereo | Right | 1 |
| | 20 | Stereo | Present | Nonstereo | Right | 1 |
| | 21 | Monocular | Present | Nonstereo | Right | 1 |
| | 22 | Stereo | Present | Nonstereo | Right | 2 |
| | 23 | Monocular | Present | Nonstereo | Right | 2 |
| | 24 | Binoptic | Present | Nonstereo | Right | 2 |
| | 25 | Monocular | Absent | Stereo | Left | 1 |
| | 26 | Stereo | Absent | Stereo | Left | 1 |
| | 27 | Binoptic | Absent | Stereo | Left | 1 |
| | 28 | Monocular | Absent | Stereo | Left | 2 |
| | 29 | Stereo | Absent | Stereo | Left | 2 |
| | 30 | Binoptic | Absent | Stereo | Left | 2 |
| | 31 | Stereo | Absent | Stereo | Right | 1 |
| | 32 | Binoptic | Absent | Stereo | Right | 1 |
| | 33 | Monocular | Absent | Stereo | Right | 1 |
| | 34 | Stereo | Absent | Stereo | Right | 2 |
| | 35 | Binoptic | Absent | Stereo | Right | 2 |
| | 36 | Monocular | Absent | Stereo | Right | 2 |
| | 37 | Binoptic | Present | Stereo | Left | 1 |
| | 38 | Stereo | Present | Stereo | Left | 1 |
| | 39 | Monocular | Present | Stereo | Left | 1 |
| | 40 | Stereo | Present | Stereo | Left | 2 |
| | 41 | Binoptic | Present | Stereo | Left | 2 |
| | 42 | Monocular | Present | Stereo | Left | 2 |
| | 43 | Stereo | Present | Stereo | Right | 1 |
| | 44 | Monocular | Present | Stereo | Right | 1 |
| | 45 | Binoptic | Present | Stereo | Right | 1 |
| | 46 | Monocular | Present | Stereo | Right | 2 |
| | 47 | Binoptic | Present | Stereo | Right | 2 |
| ↓ | 48 | Stereo | Present | Stereo | Right | 2 |

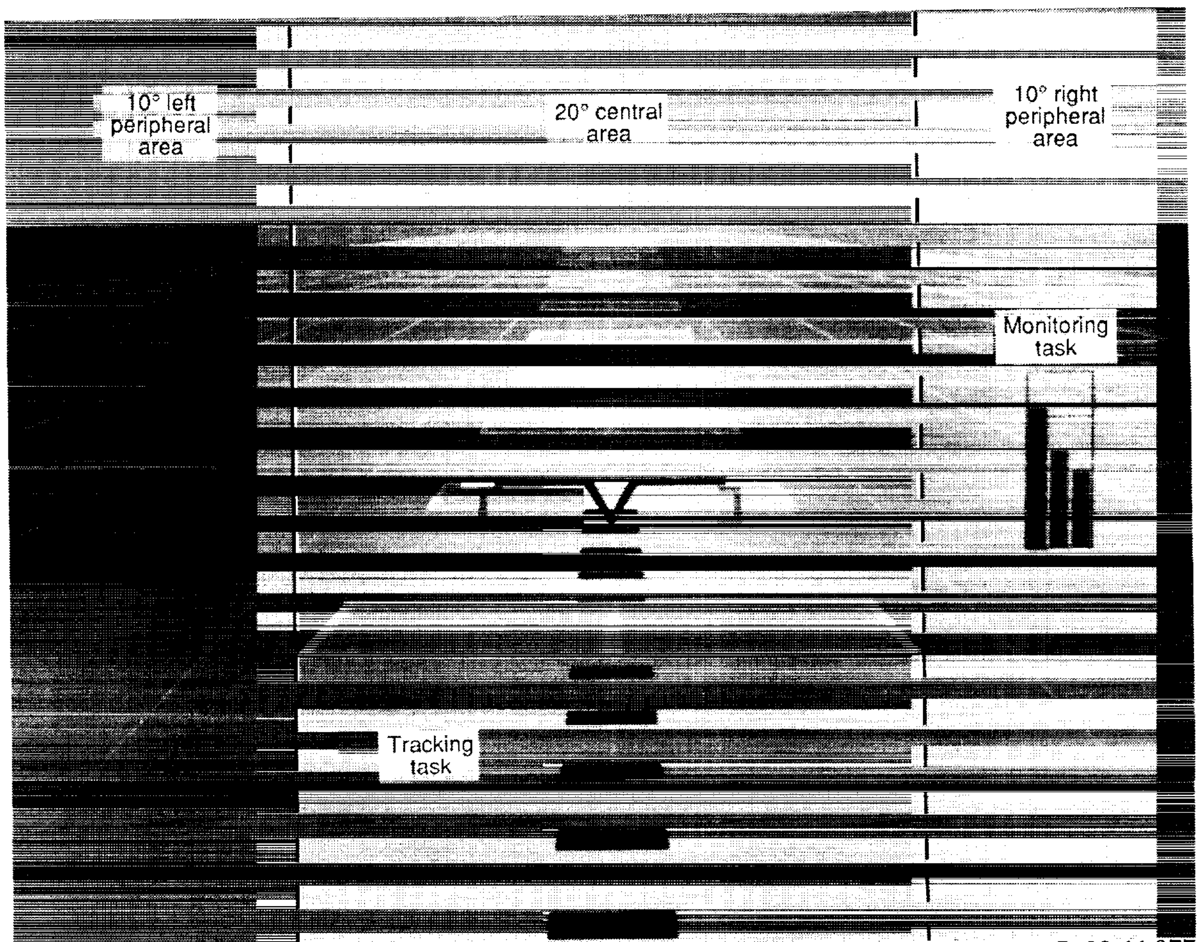
Table 1. Concluded

| Pilot | Run | Monitor condition | Color cueing | Pathway condition | Location | Replicates |
|---|---|---|---|---|---|---|
| 5 | 1 | Binoptic | Present | Nonstereo | Left | 1 |
| ↓ | 2 | Monocular | Present | Nonstereo | Left | 1 |
| | 3 | Stereo | Present | Nonstereo | Left | 1 |
| | 4 | Monocular | Present | Nonstereo | Left | 2 |
| | 5 | Binoptic | Present | Nonstereo | Left | 2 |
| | 6 | Stereo | Present | Nonstereo | Left | 2 |
| | 7 | Stereo | Present | Nonstereo | Right | 1 |
| | 8 | Binoptic | Present | Nonstereo | Right | 1 |
| | 9 | Monocular | Present | Nonstereo | Right | 1 |
| | 10 | Stereo | Present | Nonstereo | Right | 2 |
| | 11 | Monocular | Present | Nonstereo | Right | 2 |
| | 12 | Binoptic | Present | Nonstereo | Right | 2 |
| | 13 | Stereo | Absent | Nonstereo | Left | 1 |
| | 14 | Monocular | Absent | Nonstereo | Left | 1 |
| | 15 | Binoptic | Absent | Nonstereo | Left | 1 |
| | 16 | Monocular | Absent | Nonstereo | Left | 2 |
| | 17 | Binoptic | Absent | Nonstereo | Left | 2 |
| | 18 | Stereo | Absent | Nonstereo | Left | 2 |
| | 19 | Stereo | Absent | Nonstereo | Right | 1 |
| | 20 | Monocular | Absent | Nonstereo | Right | 1 |
| | 21 | Binoptic | Absent | Nonstereo | Right | 1 |
| | 22 | Monocular | Absent | Nonstereo | Right | 2 |
| | 23 | Stereo | Absent | Nonstereo | Right | 2 |
| | 24 | Binoptic | Absent | Nonstereo | Right | 2 |
| | 25 | Binoptic | Present | Stereo | Left | 1 |
| | 26 | Stereo | Present | Stereo | Left | 1 |
| | 27 | Monocular | Present | Stereo | Left | 1 |
| | 28 | Binoptic | Present | Stereo | Left | 2 |
| | 29 | Monocular | Present | Stereo | Left | 2 |
| | 30 | Stereo | Present | Stereo | Left | 2 |
| | 31 | Stereo | Present | Stereo | Right | 1 |
| | 32 | Monocular | Present | Stereo | Right | 1 |
| | 33 | Binoptic | Present | Stereo | Right | 1 |
| | 34 | Monocular | Present | Stereo | Right | 2 |
| | 35 | Stereo | Present | Stereo | Right | 2 |
| | 36 | Binoptic | Present | Stereo | Right | 2 |
| | 37 | Stereo | Absent | Stereo | Left | 1 |
| | 38 | Binoptic | Absent | Stereo | Left | 1 |
| | 39 | Monocular | Absent | Stereo | Left | 1 |
| | 40 | Binoptic | Absent | Stereo | Left | 2 |
| | 41 | Stereo | Absent | Stereo | Left | 2 |
| | 42 | Monocular | Absent | Stereo | Left | 2 |
| | 43 | Stereo | Absent | Stereo | Right | 1 |
| | 44 | Monocular | Absent | Stereo | Right | 1 |
| | 45 | Binoptic | Absent | Stereo | Right | 1 |
| | 46 | Monocular | Absent | Stereo | Right | 2 |
| | 47 | Binoptic | Absent | Stereo | Right | 2 |
| | 48 | Stereo | Absent | Stereo | Right | 2 |

Table 2. Summary of Analyses of Variance

| Factors | Degrees of freedom | Significance[a] of tracking task performance measures of— | | | | | Significance[a] of monitoring task performance measures of— | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean altitude error | Standard deviation of altitude error | rms altitude error | Pitch control input | Collective control input | Percent excursions detected | Extraneous reports | Response time |
| Pilot, $P$ | 4 | ** | ** | ** | ** | ** | ** | ** | ** |
| Monitor condition, $M$ | 2 | – | – | – | – | – | ** | – | ** |
| Color cueing, $C$ | 1 | ** | ** | ** | – | – | ** | ** | – |
| Pathway condition, $T$ | 1 | ** | ** | ** | ** | ** | – | – | ** |
| Location, $L$ | 1 | * | * | ** | – | ** | – | – | – |
| Replicates, $R$ | 1 | – | – | – | – | – | – | – | – |
| $P \times M$ | 8 | – | – | – | – | – | * | – | – |
| $P \times C$ | 4 | ** | * | * | – | ** | * | ** | ** |
| $P \times T$ | 4 | – | – | – | ** | ** | * | – | * |
| $P \times L$ | 4 | – | – | – | * | ** | – | – | – |
| $M \times C$ | 2 | – | – | – | – | – | – | – | – |
| $M \times T$ | 2 | – | – | – | – | – | – | – | – |
| $M \times L$ | 2 | – | – | – | – | – | – | – | – |
| $C \times T$ | 1 | ** | ** | ** | – | – | – | – | – |
| $C \times L$ | 1 | – | – | – | – | – | – | – | – |
| $T \times L$ | 1 | – | – | – | – | – | – | – | – |
| $P \times C \times T$ | 4 | – | * | * | – | – | – | – | – |
| $P \times T \times L$ | 4 | – | – | – | * | – | – | – | – |
| Error | 192 | | | | | | | | |

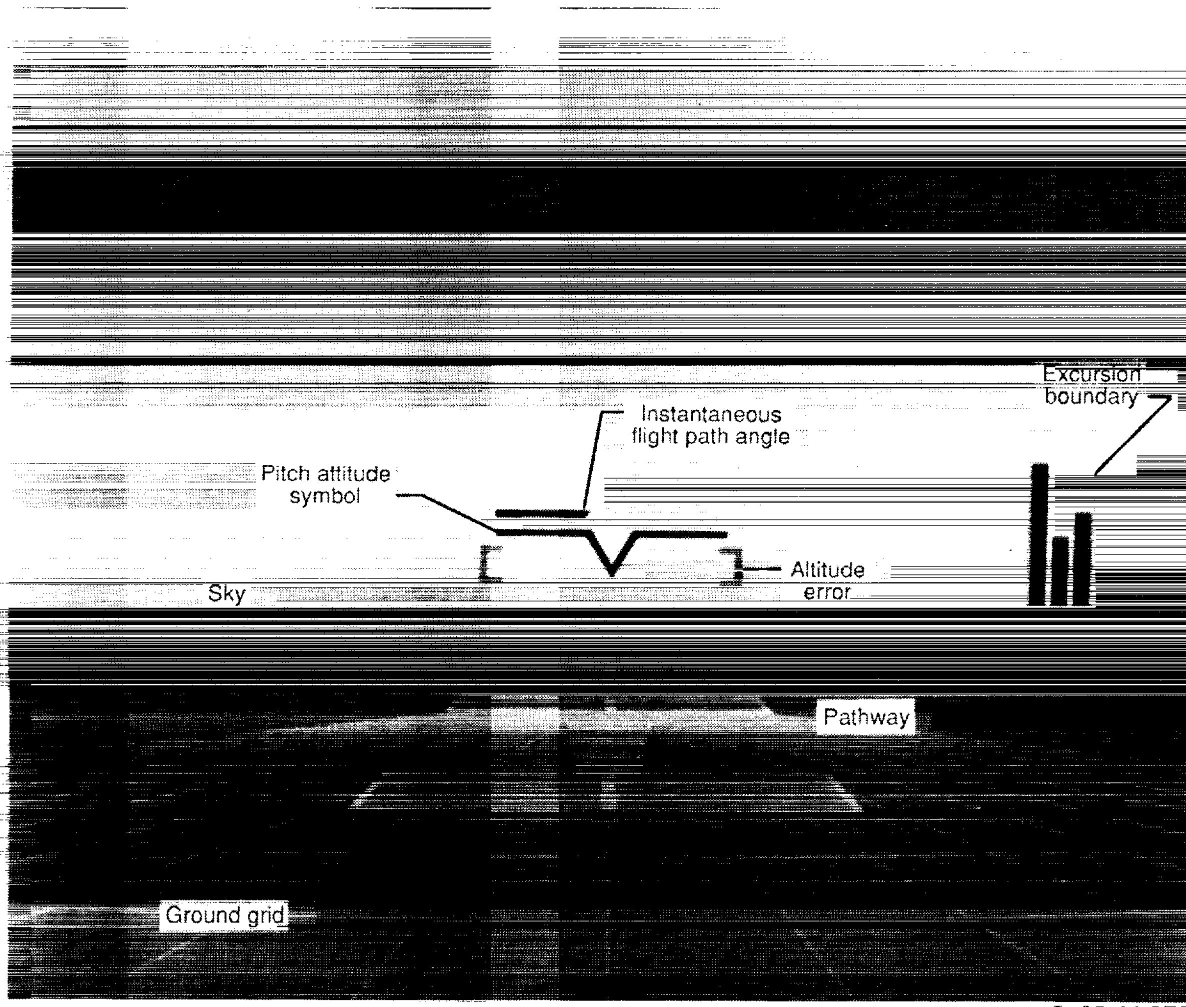
[a] Significance:
– Not significant at levels considered.
* Significant at 5-percent level.
** Significant at 1-percent level.




L-89-11 977

(a) Presentation of tasks.

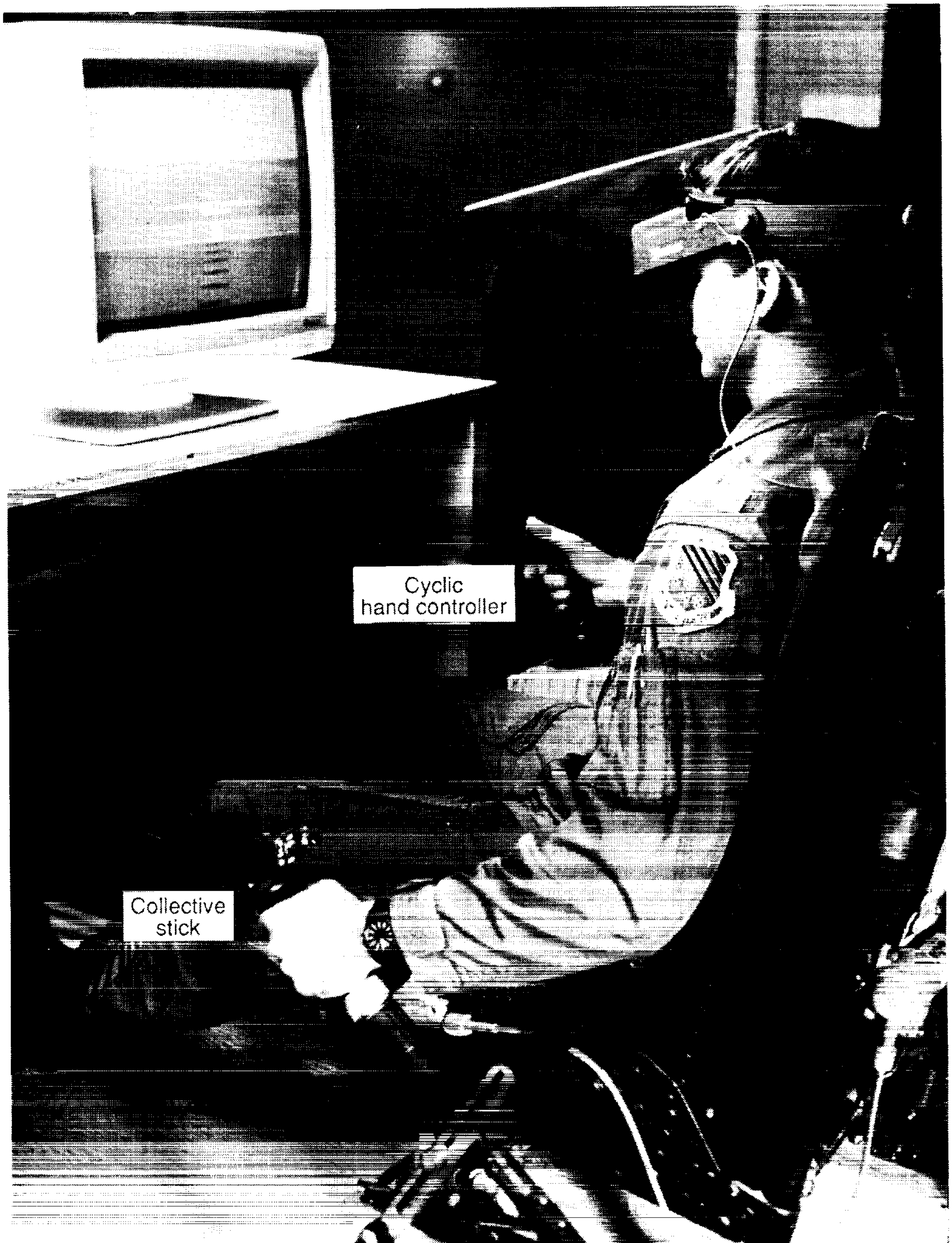
Figure 1. Display format of studies.



L-89-11 976

(b) Display symbology.

Figure 1. Concluded.



L-89-6689

Figure 2. Pilot workstation.

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BLACK AND WHITE PHOTOGRAPH

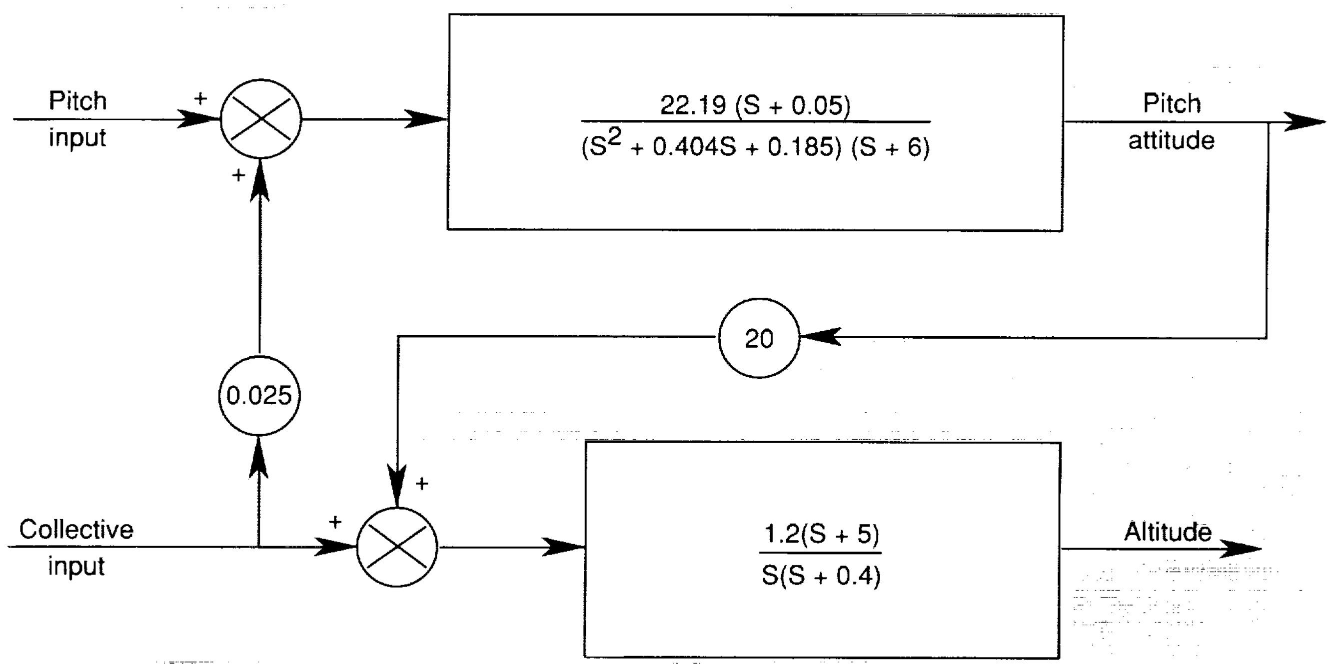
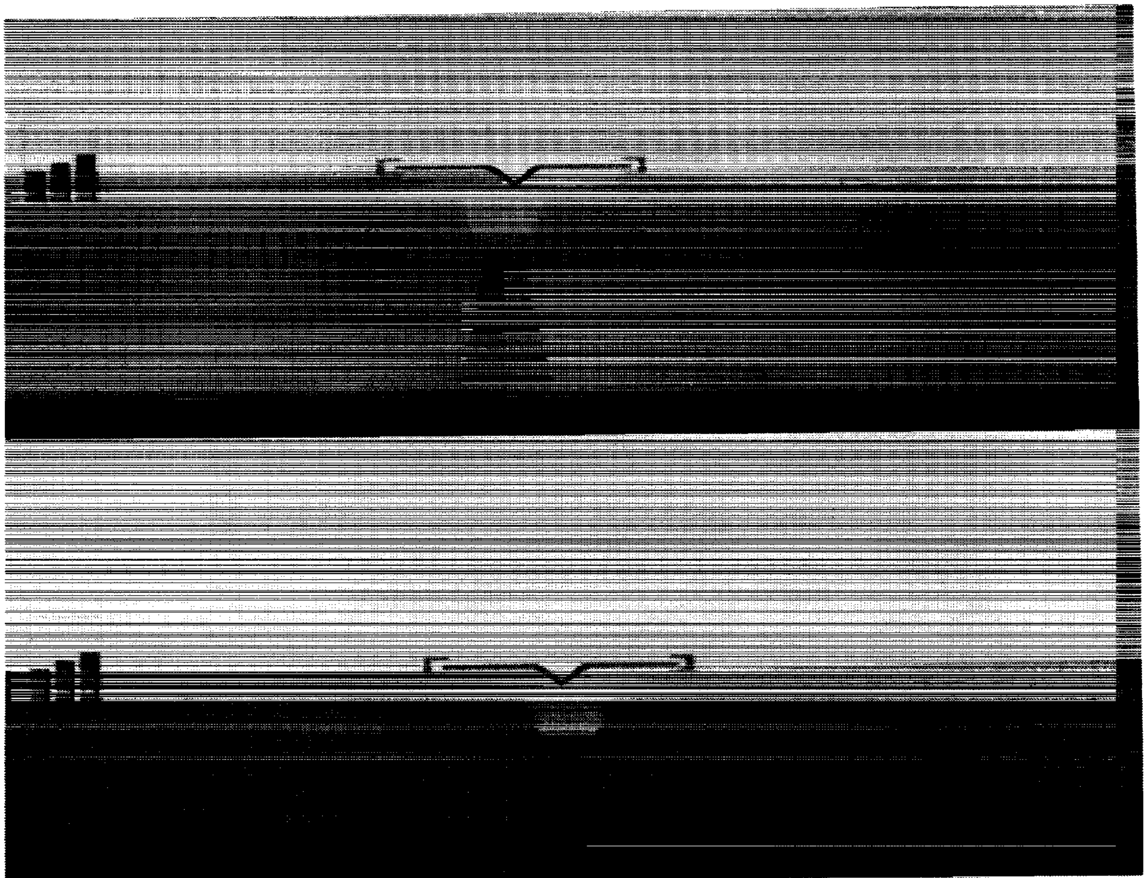
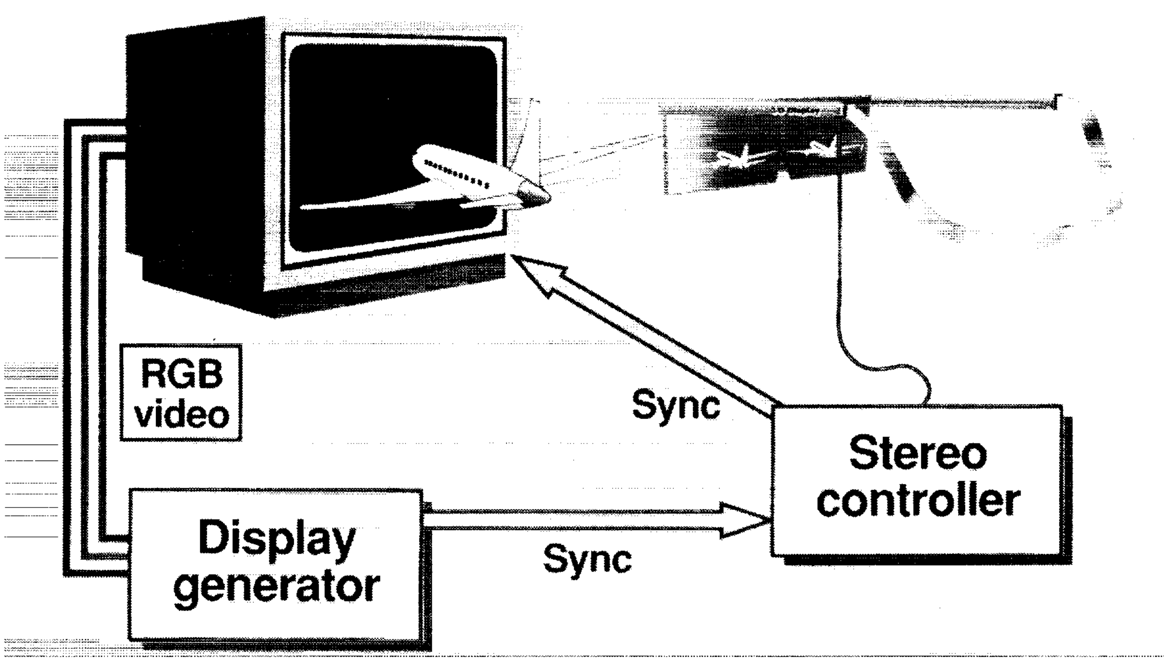



Figure 3. Block diagram of modified helicopter model (two degrees of freedom).



L-89-6671

Figure 4. Stereo pair for stereo pathway and binoptic monitoring task display condition.




L-89-8776

Figure 5. Hardware for stereo 3-D flight display.

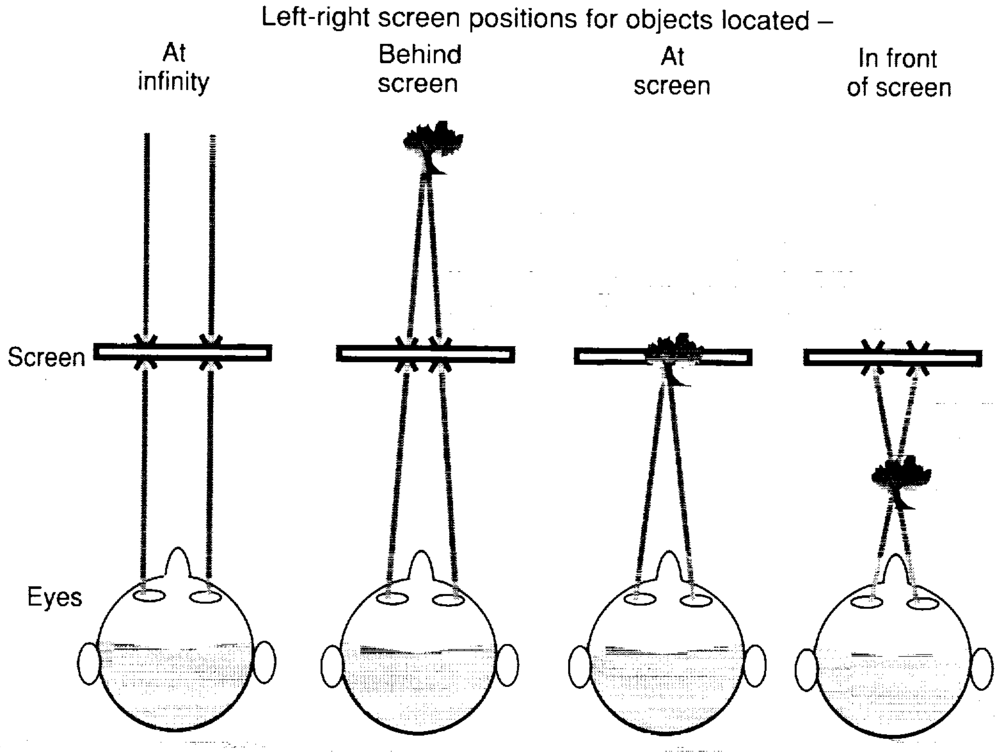



Figure 6. Geometric principle of stereo displays.

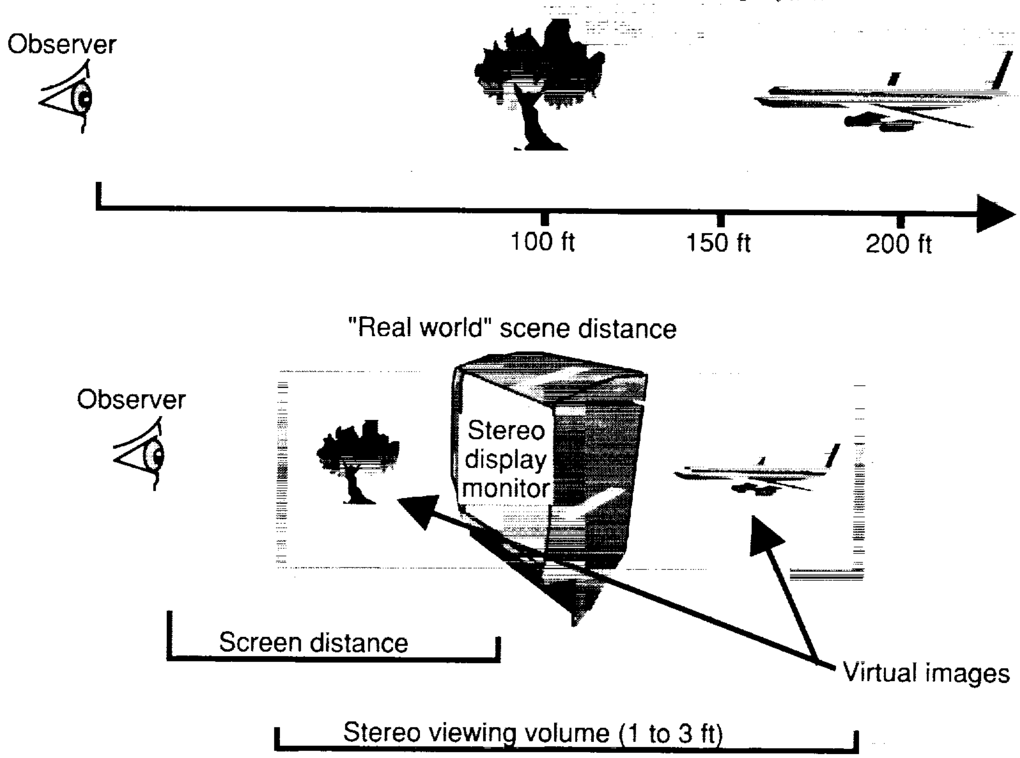



Figure 7. Scene-to-screen mapping with conventional stereo technology.

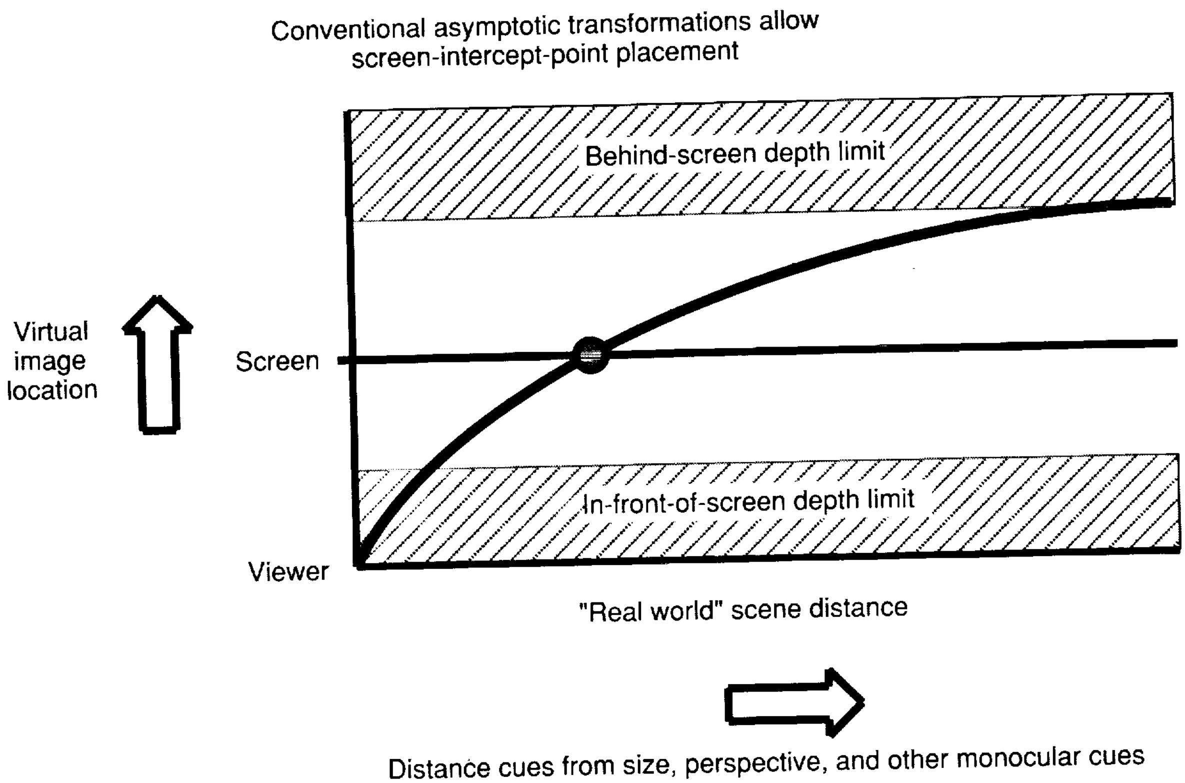



Figure 8. Conventional visual scene mapping into stereo 3-D viewing volumes.

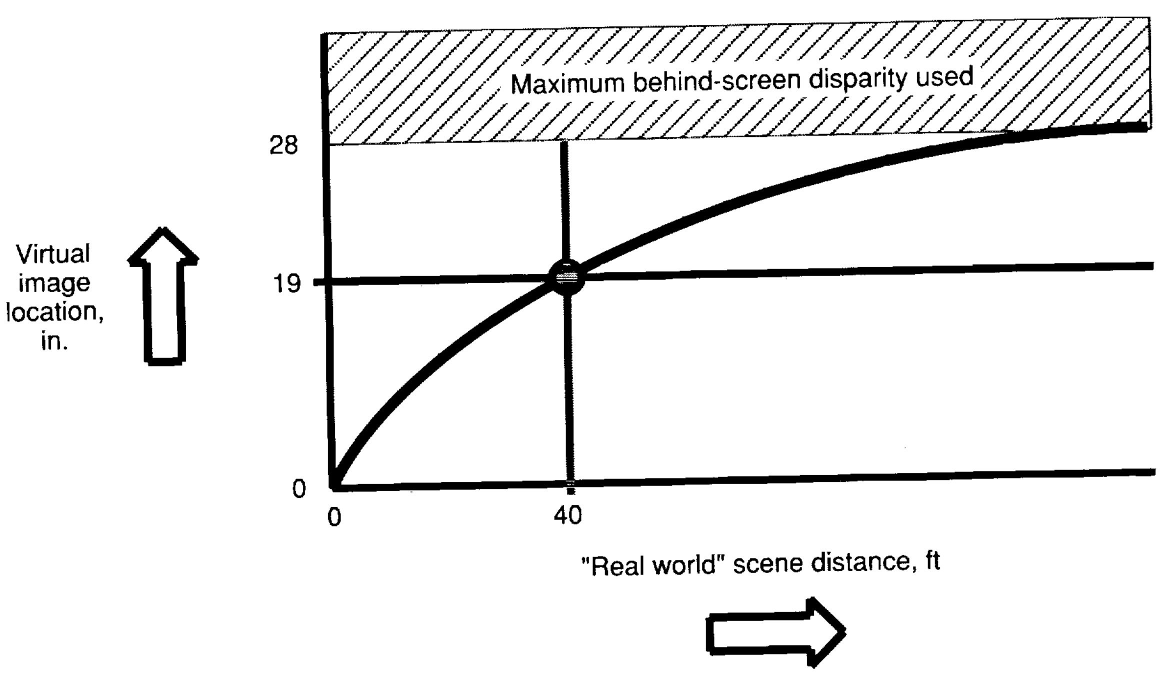



Figure 9. Visual scene mapping into stereo 3-D viewing volume for this study.

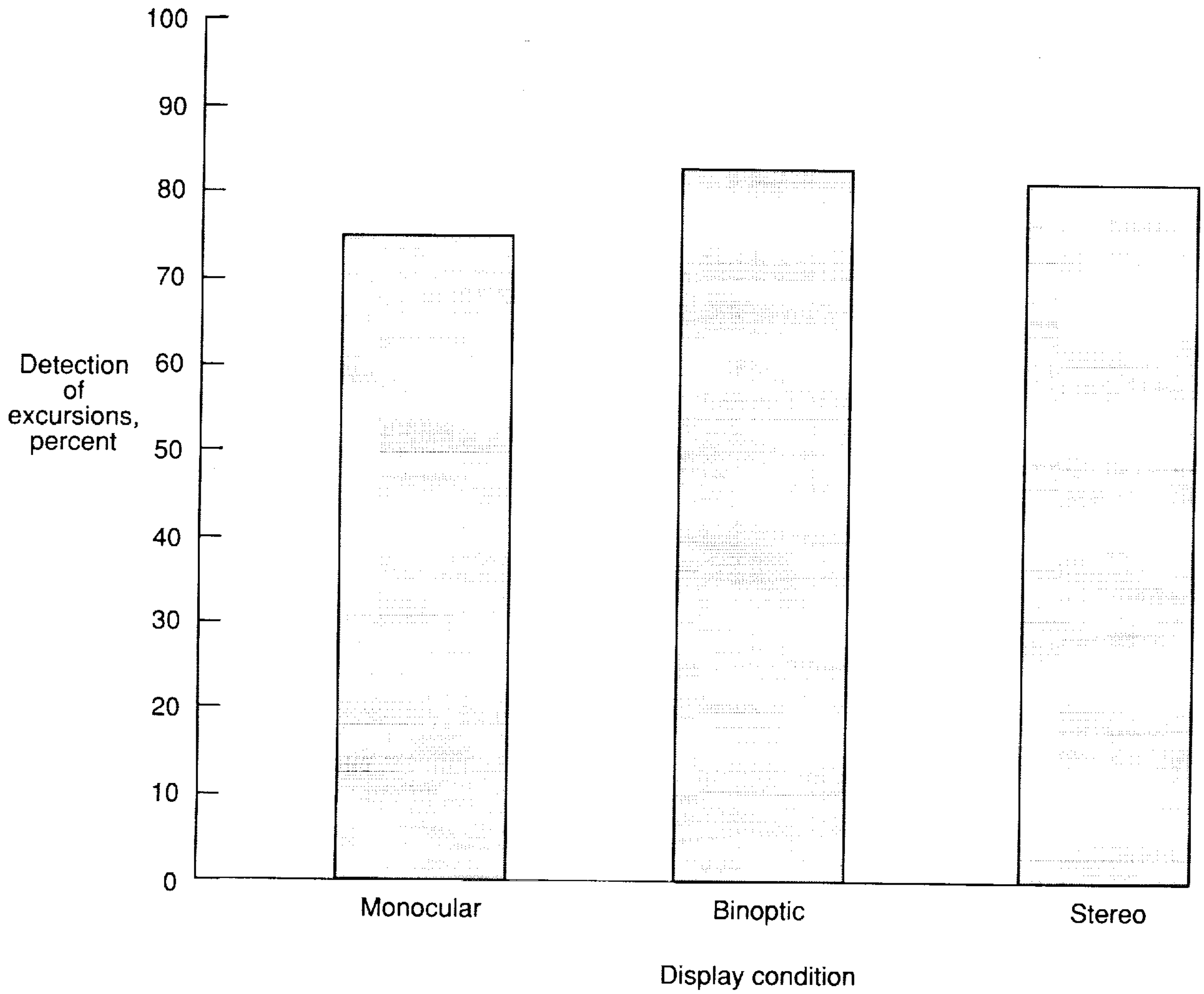



Figure 10. Effect of monitoring task display condition on detection of boundary excursions for all pilots.

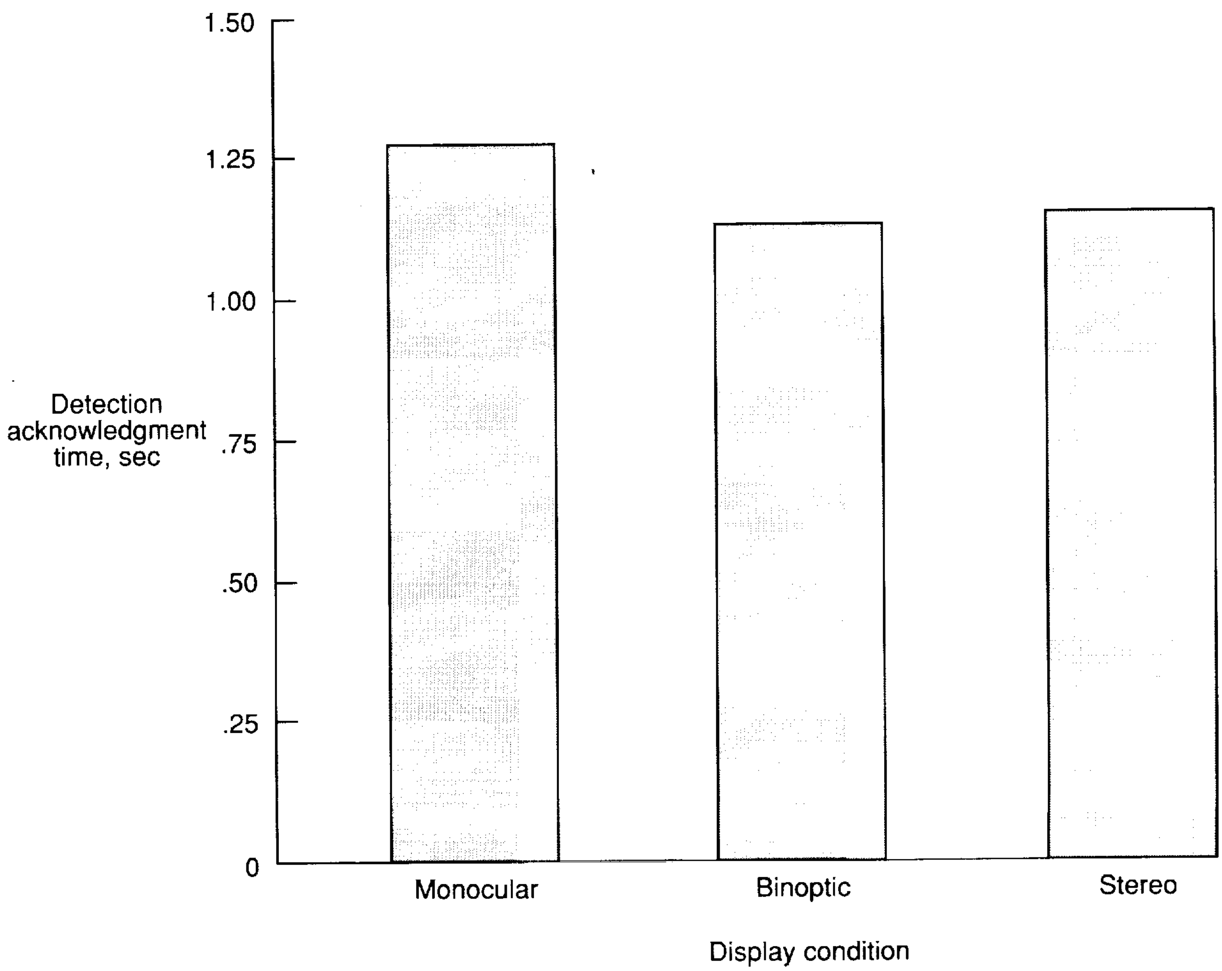



Figure 11. Effect of monitoring task display condition on acknowledgment time for detection of excursions for all pilots.

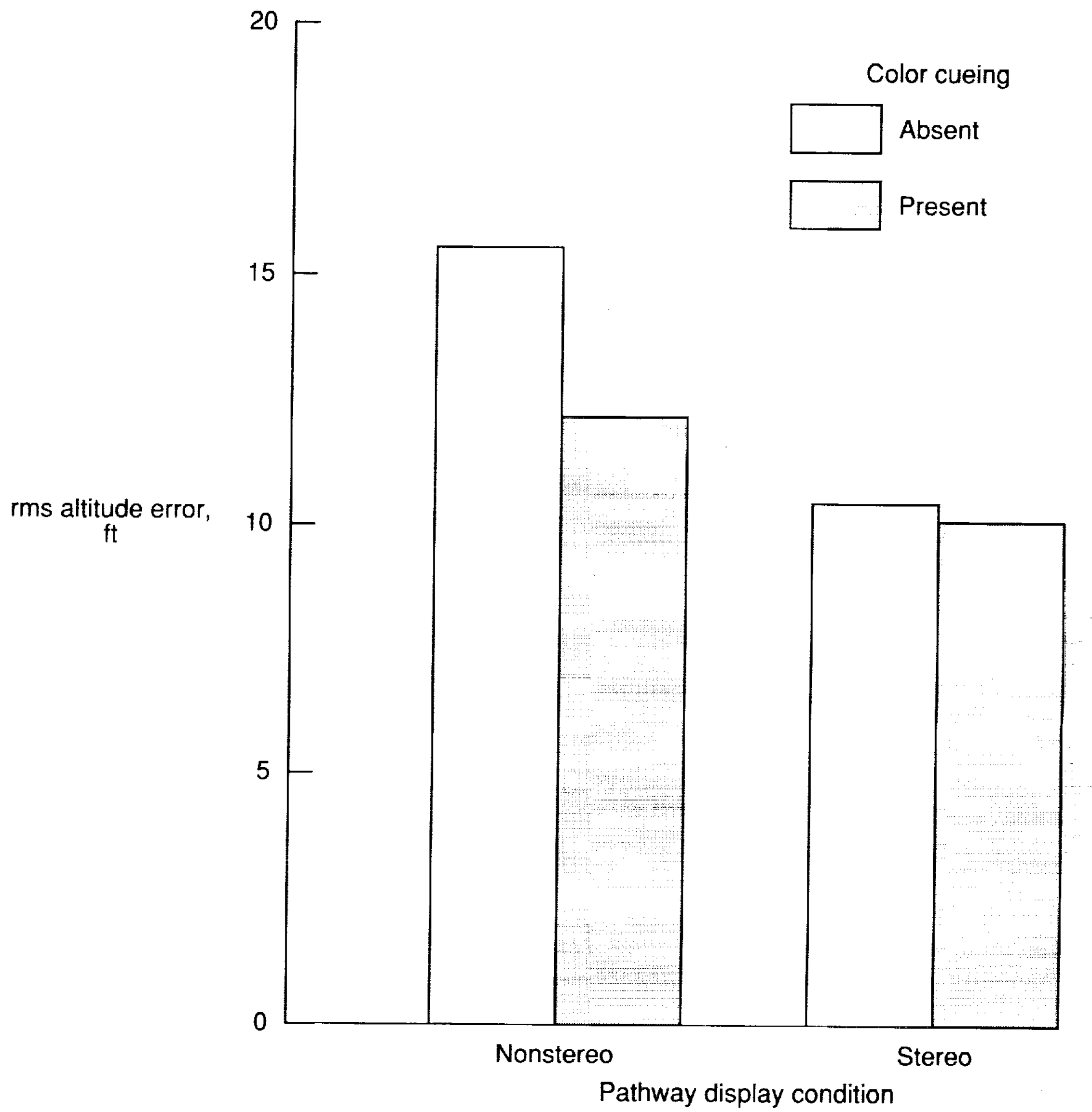
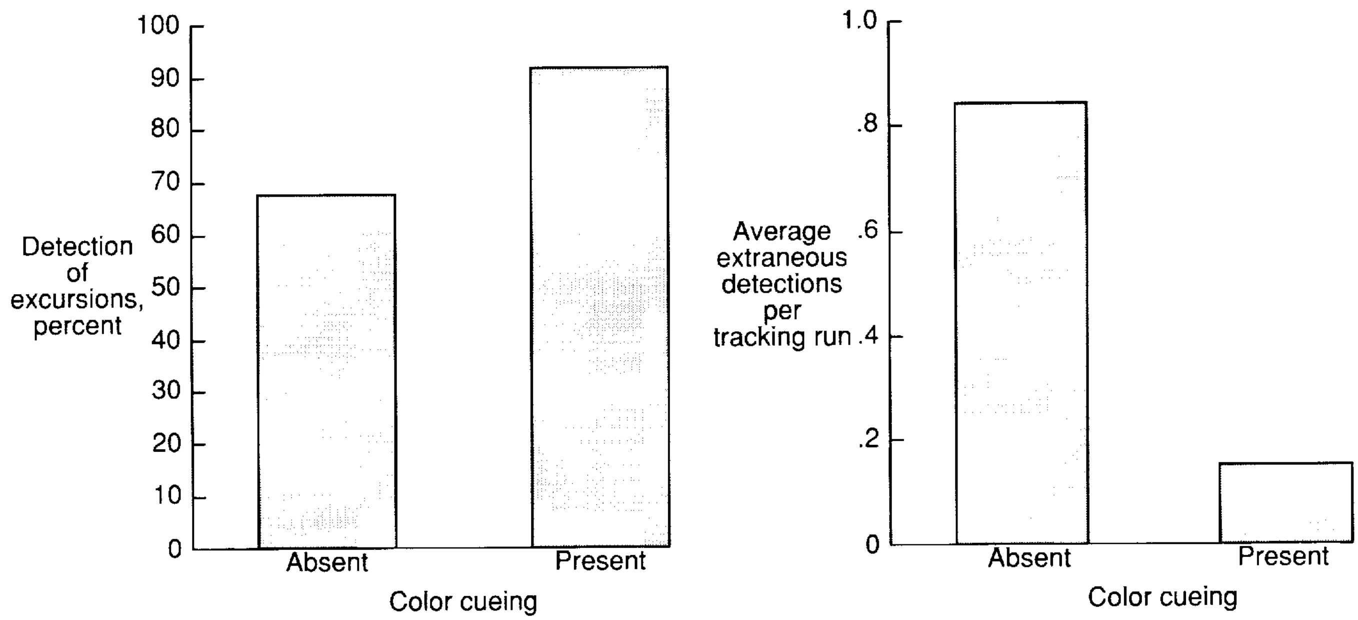



Figure 12. Effect of color cueing in monitoring task display on rms altitude error for tracking task across tracking task pathway display conditions for all pilots.




(a) Effect of color cueing in monitoring task display on detection percentage for monitoring task.

(b) Effect of color cueing in monitoring task display on extraneous detections for monitoring task.

Figure 13. Monitoring task performance effects for color cueing condition for all pilots.

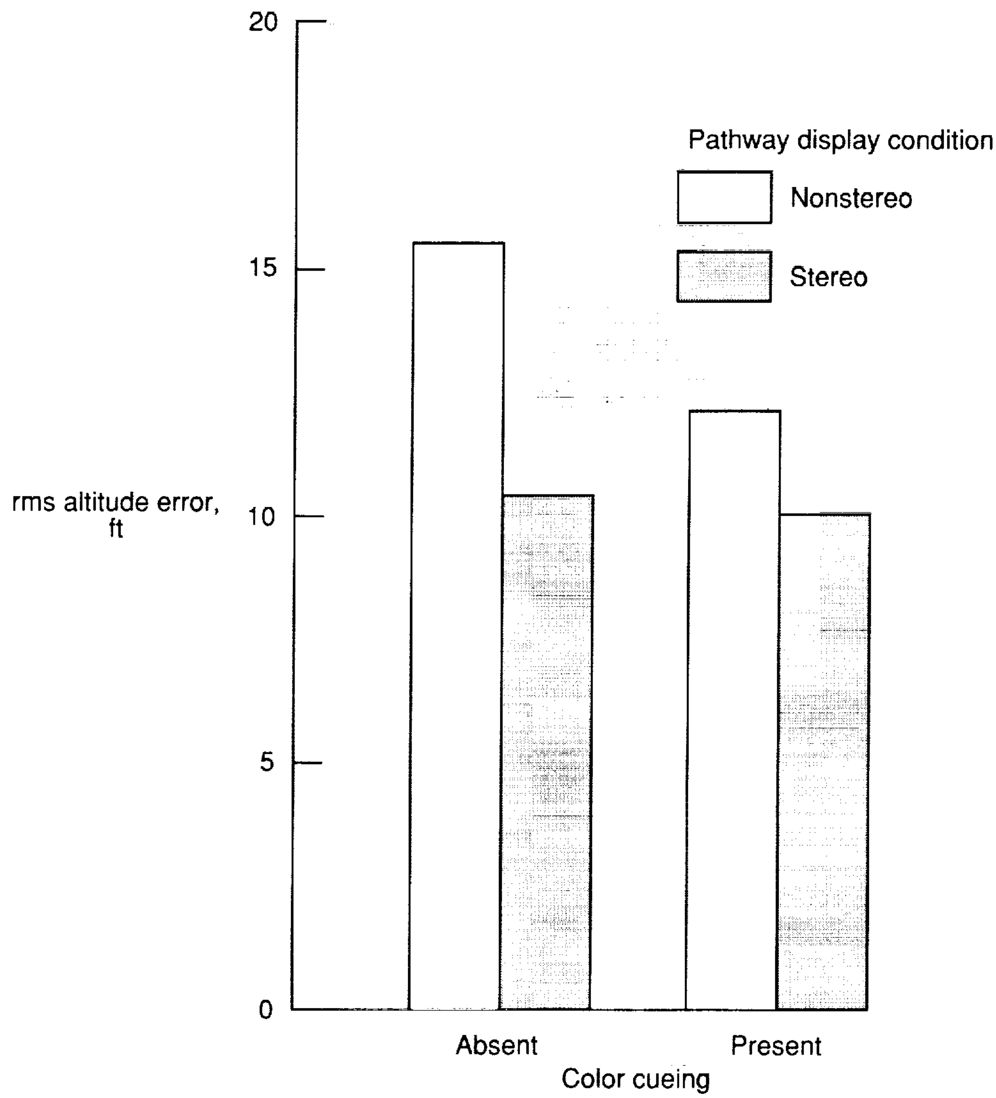



Figure 14. Effect of tracking task pathway display condition on rms altitude error for tracking task across color cueing in monitoring task display for all pilots.

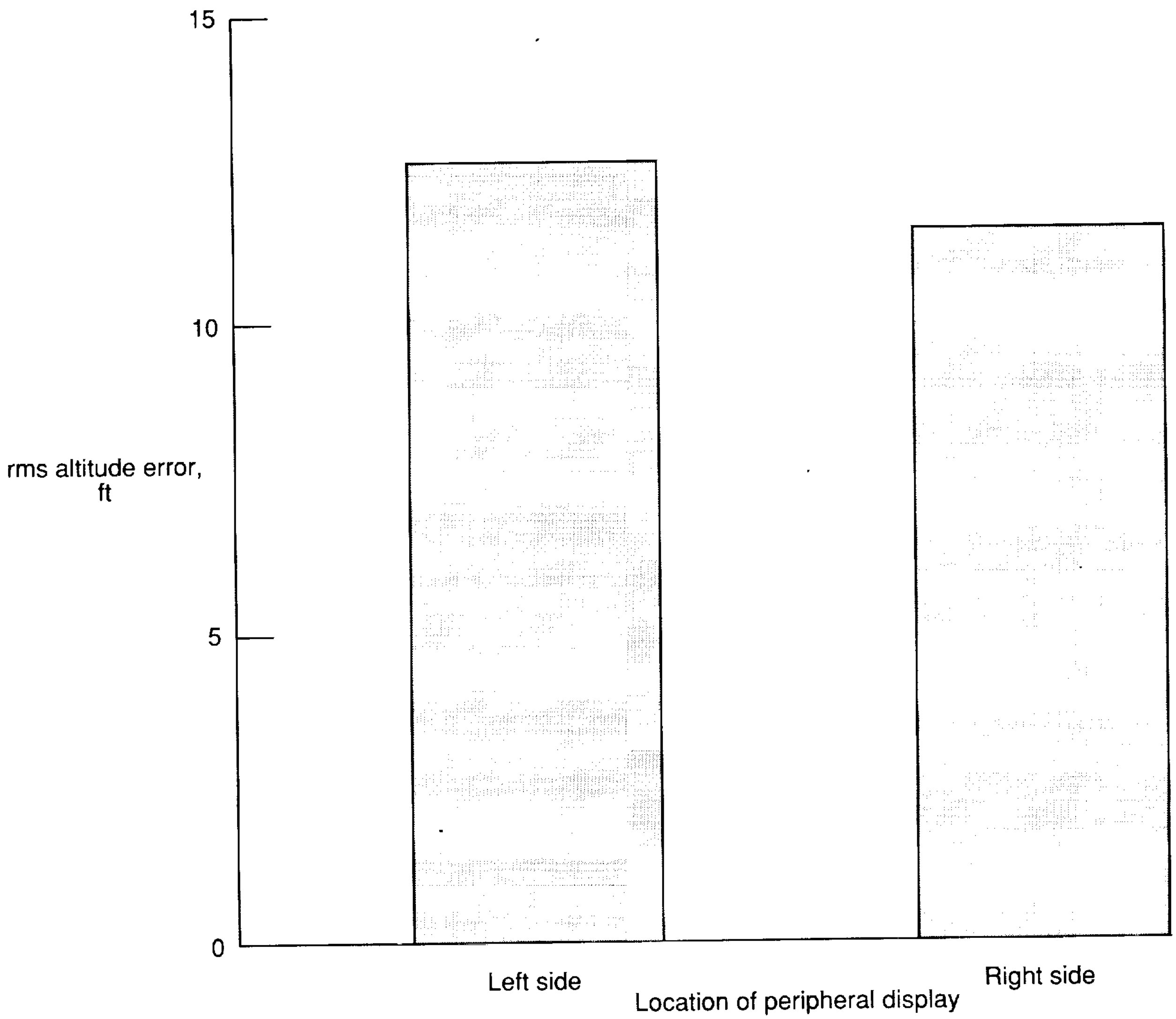



Figure 15. Effect of location of peripheral area display for monitoring task on rms altitude error for tracking task for all pilots.

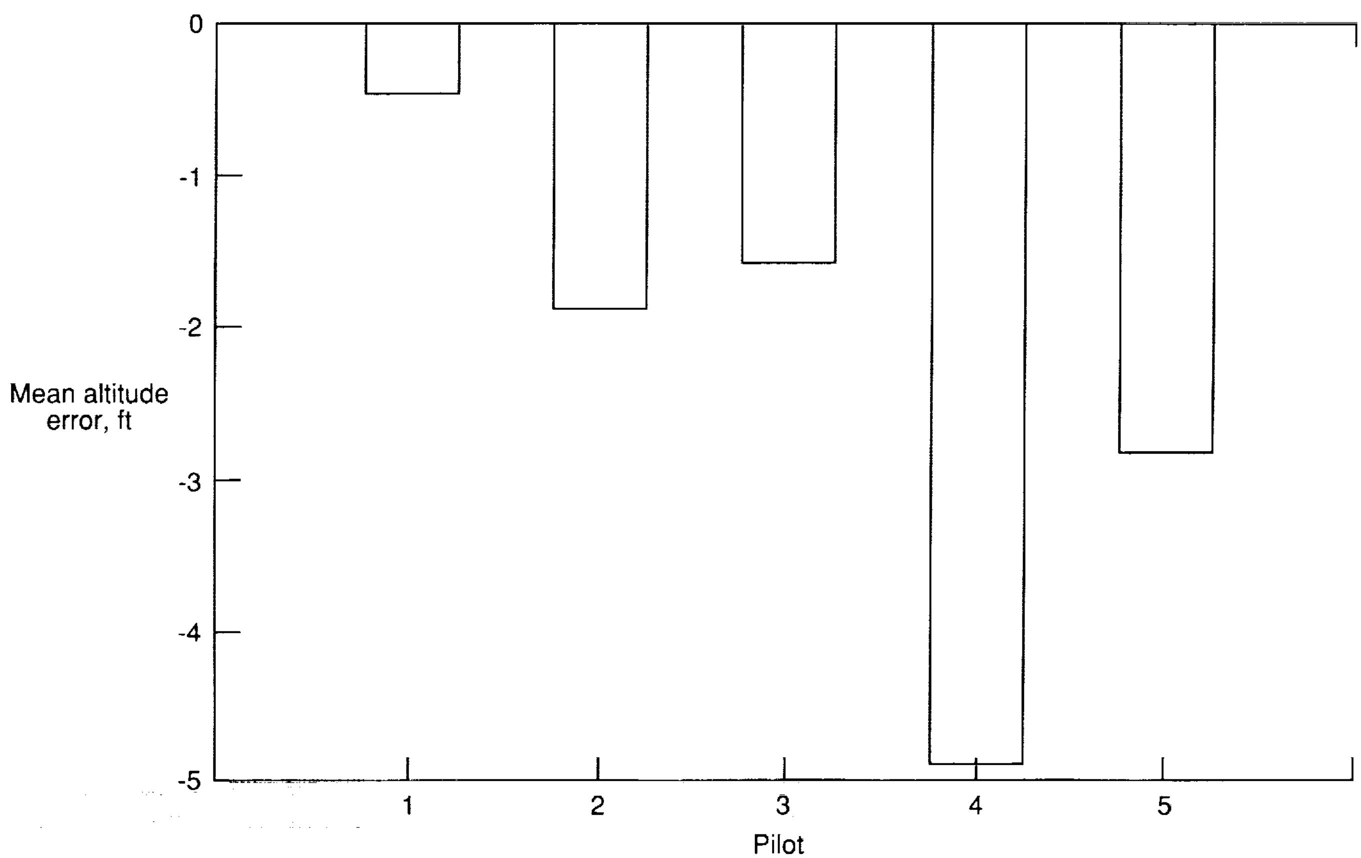



Figure 16. Mean altitude error of each pilot for tracking task.

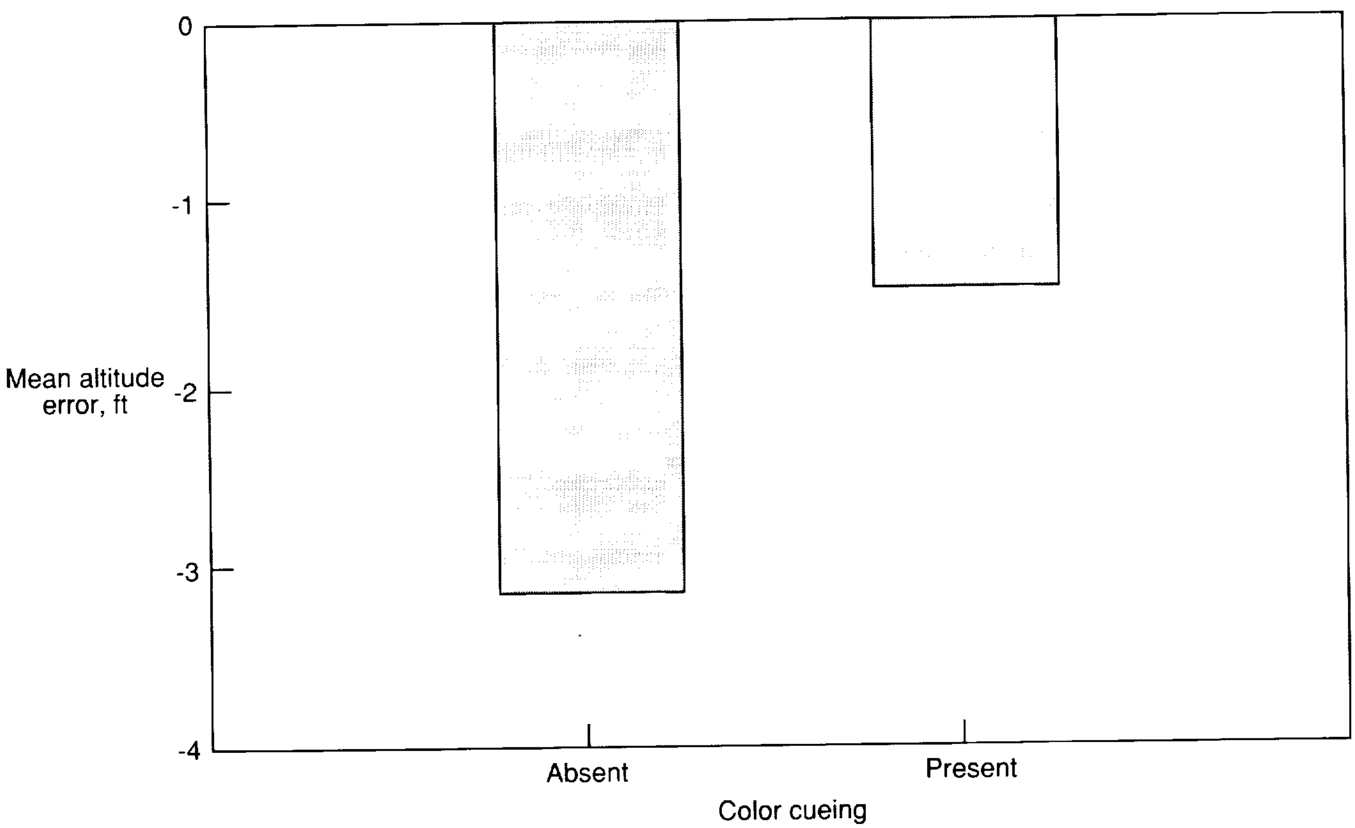



Figure 17. Effect of color cueing in monitoring task display on mean altitude error for tracking task for all pilots.

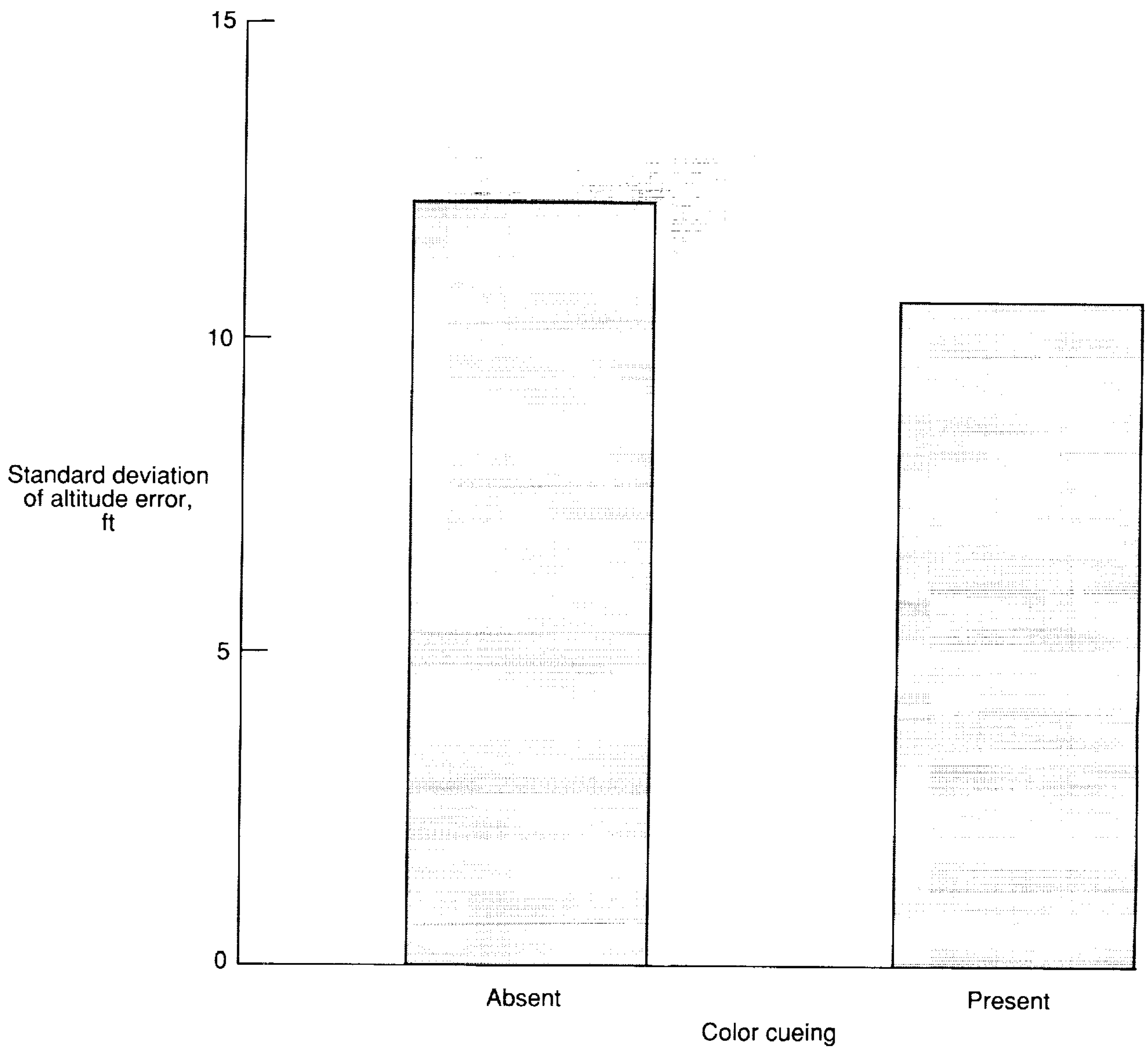



Figure 18. Effect of color cueing in monitoring task display on standard deviation of altitude error for tracking task for all pilots.

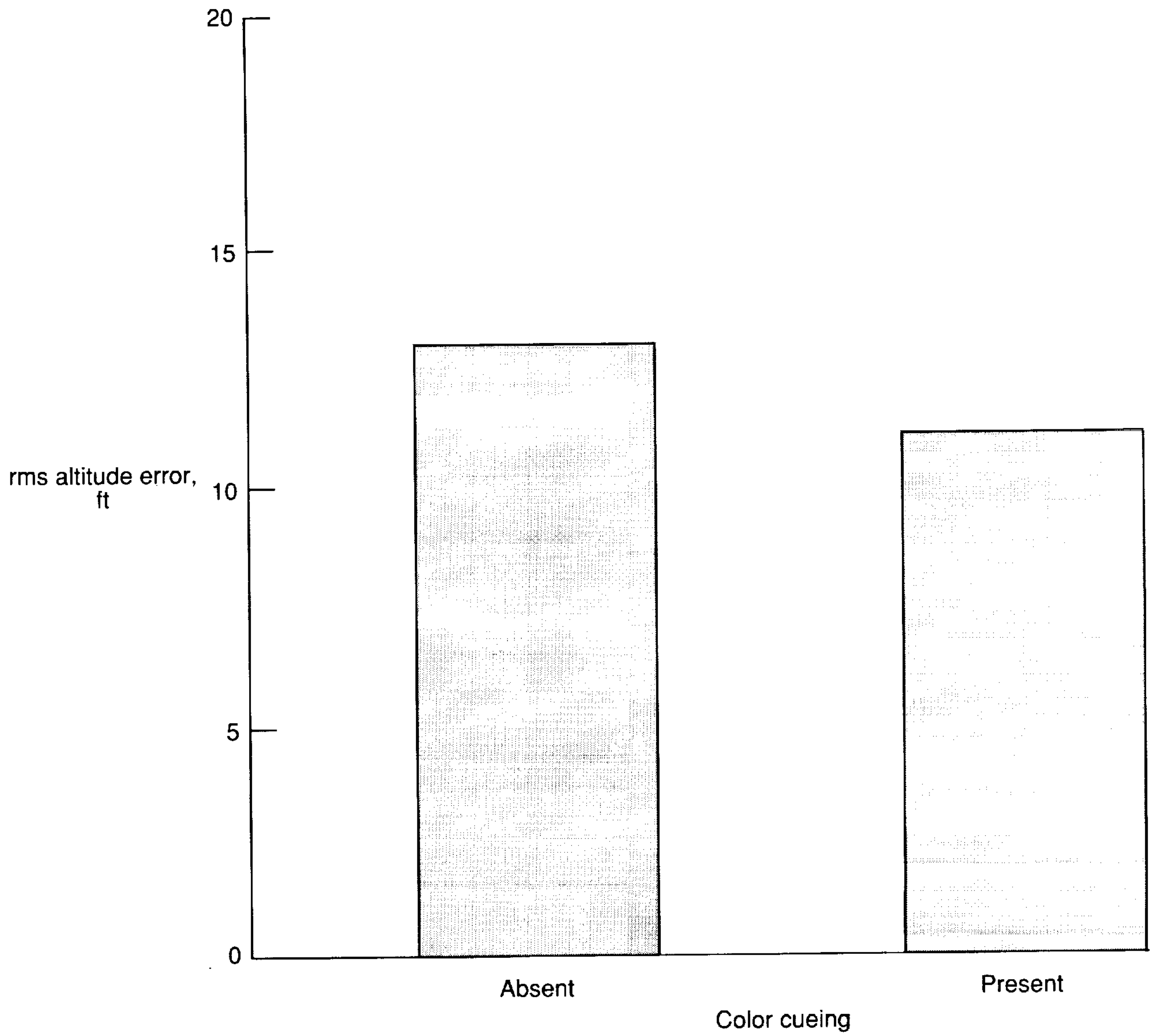



Figure 19. Effect of color cueing in monitoring task display on rms altitude error for tracking task for all pilots.

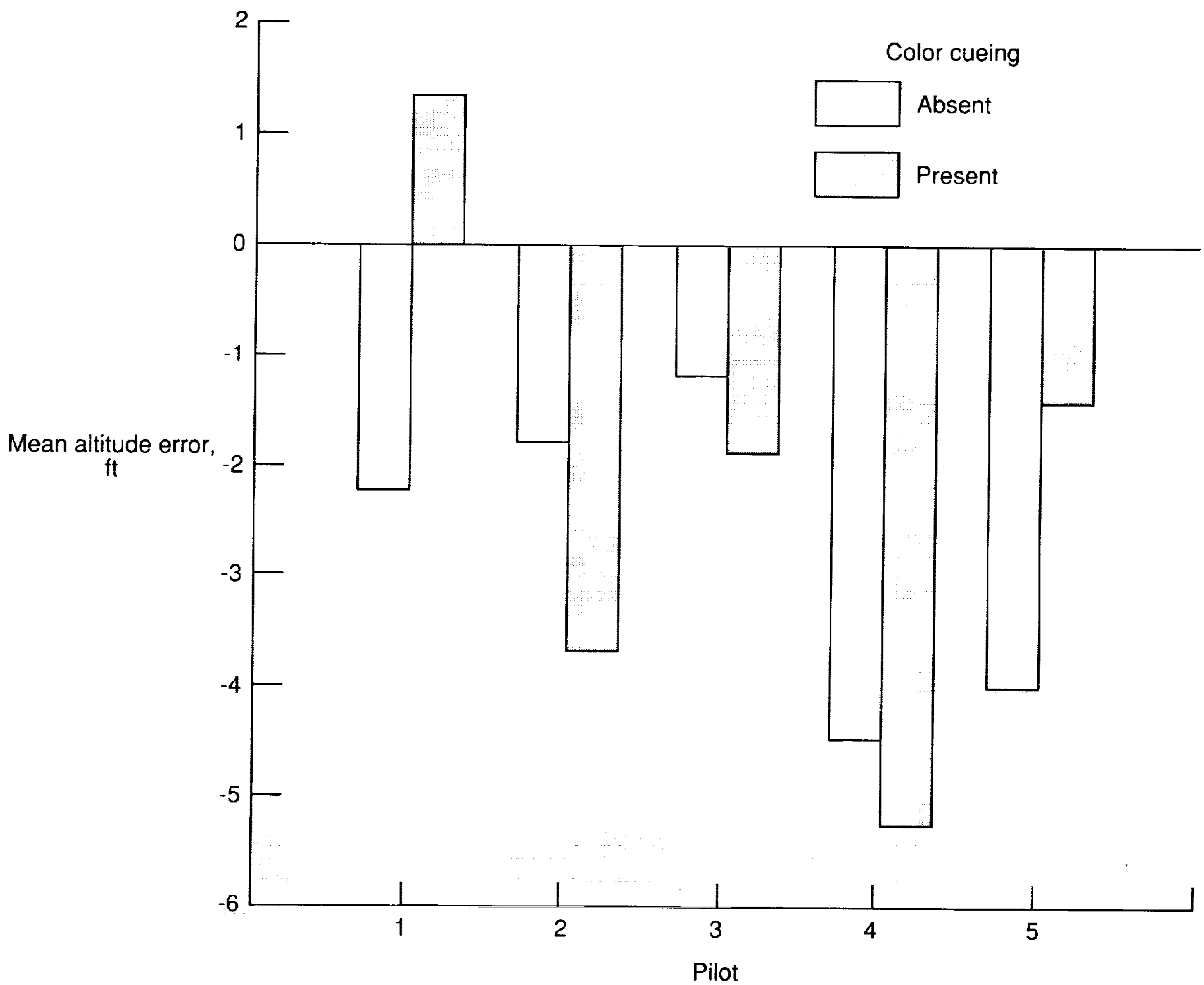



Figure 20. Effect of color cueing in monitoring task display on mean altitude error for tracking task for each pilot.

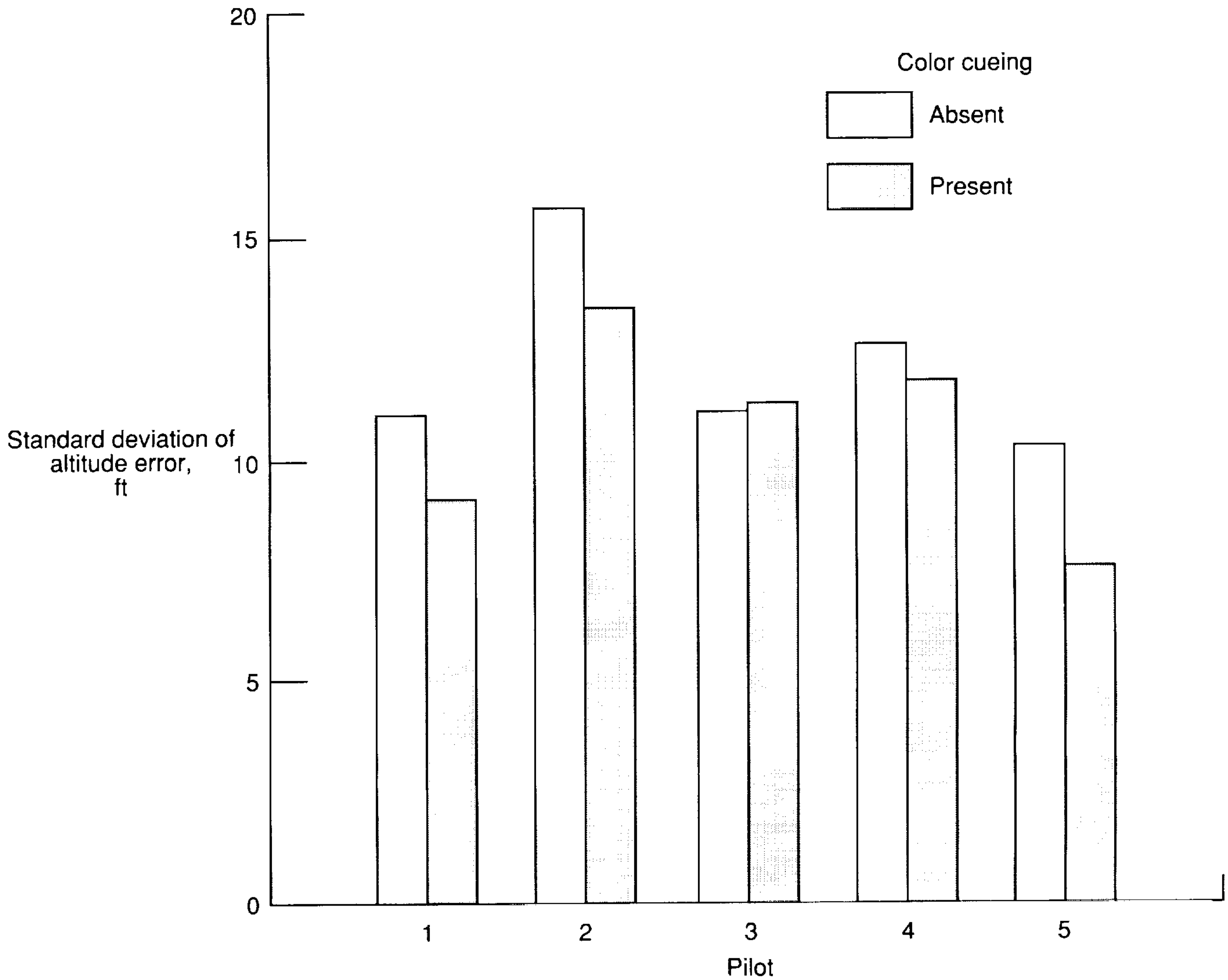



Figure 21. Effect of color cueing in monitoring task display on standard deviation of altitude error for tracking task for each pilot.

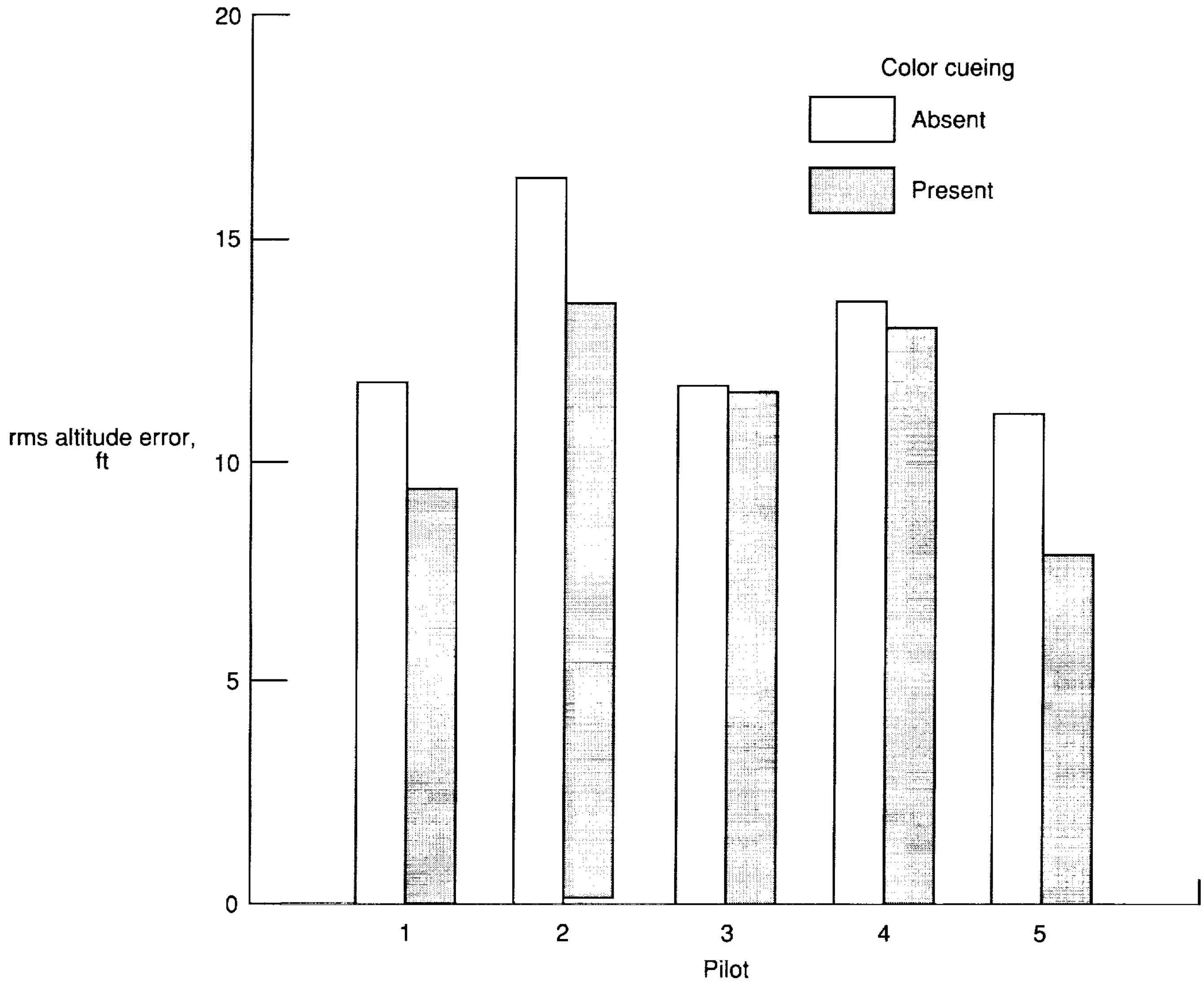



Figure 22. Effect of color cueing in monitoring task display on rms altitude error for tracking task for each pilot.

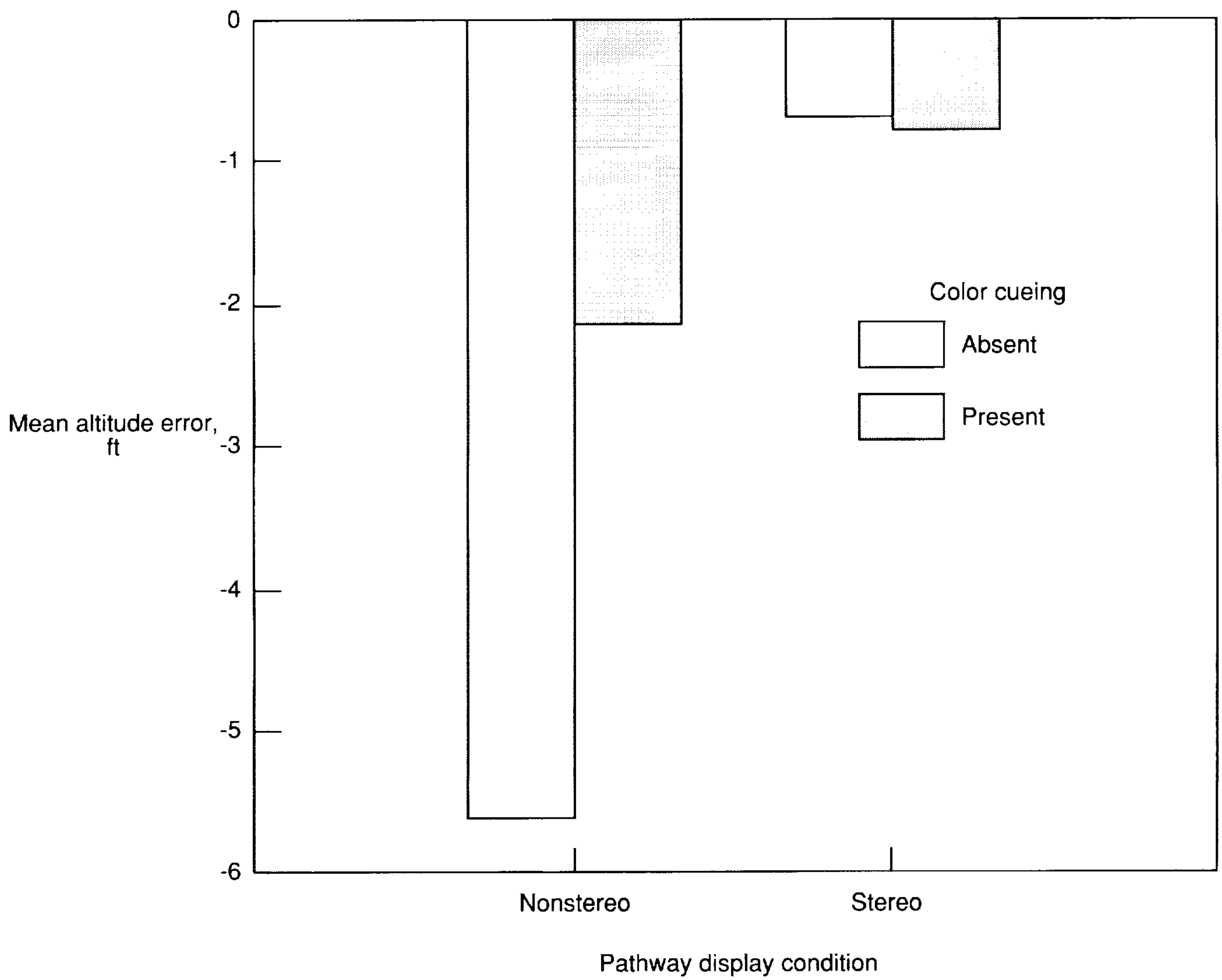



Figure 23. Effect of color cueing in monitoring task display on mean altitude error for tracking task across tracking task pathway display conditions for all pilots.

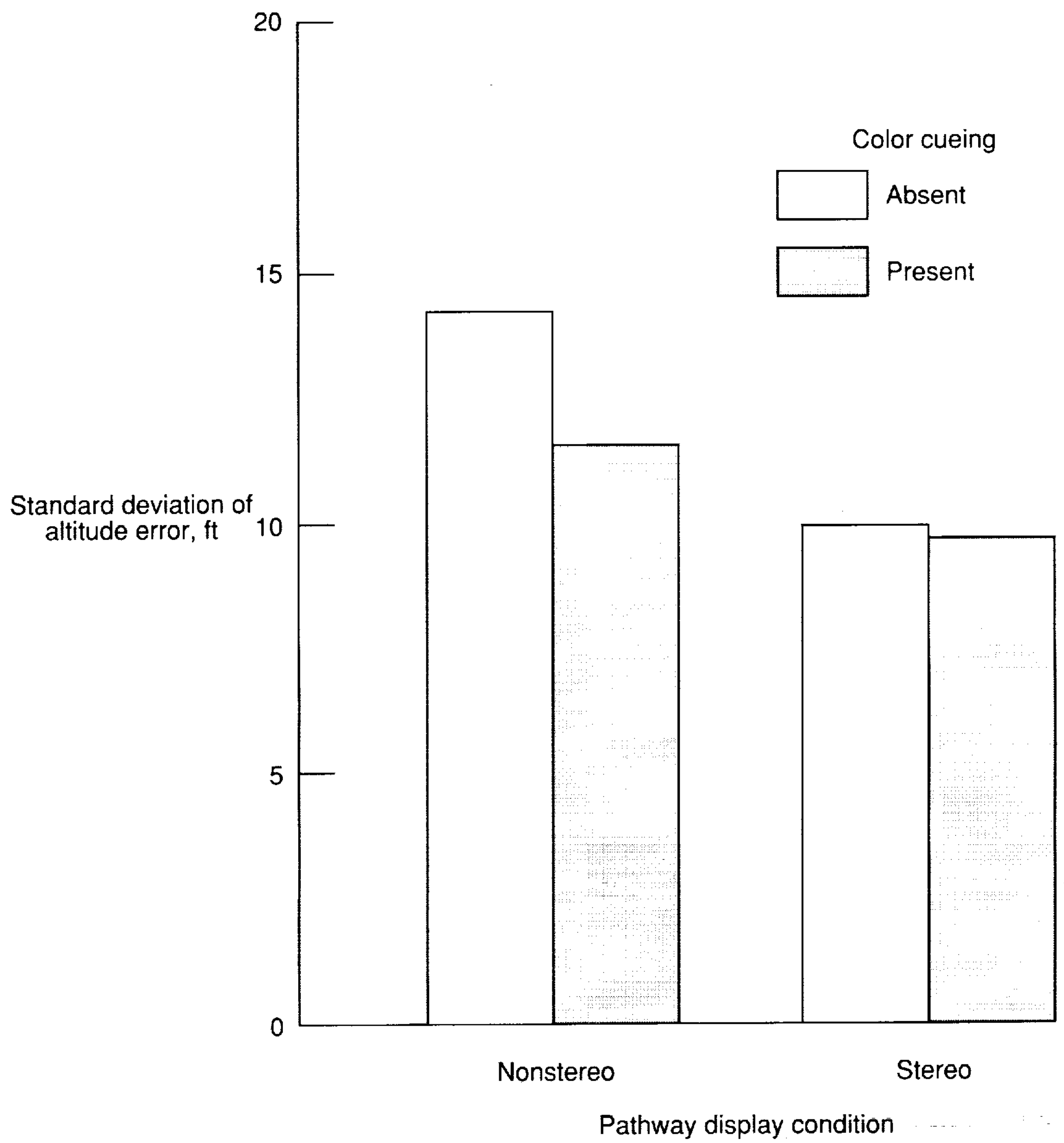



Figure 24. Effect of color cueing in monitoring task display on standard deviation of altitude error for tracking task across tracking task pathway display condition for all pilots.

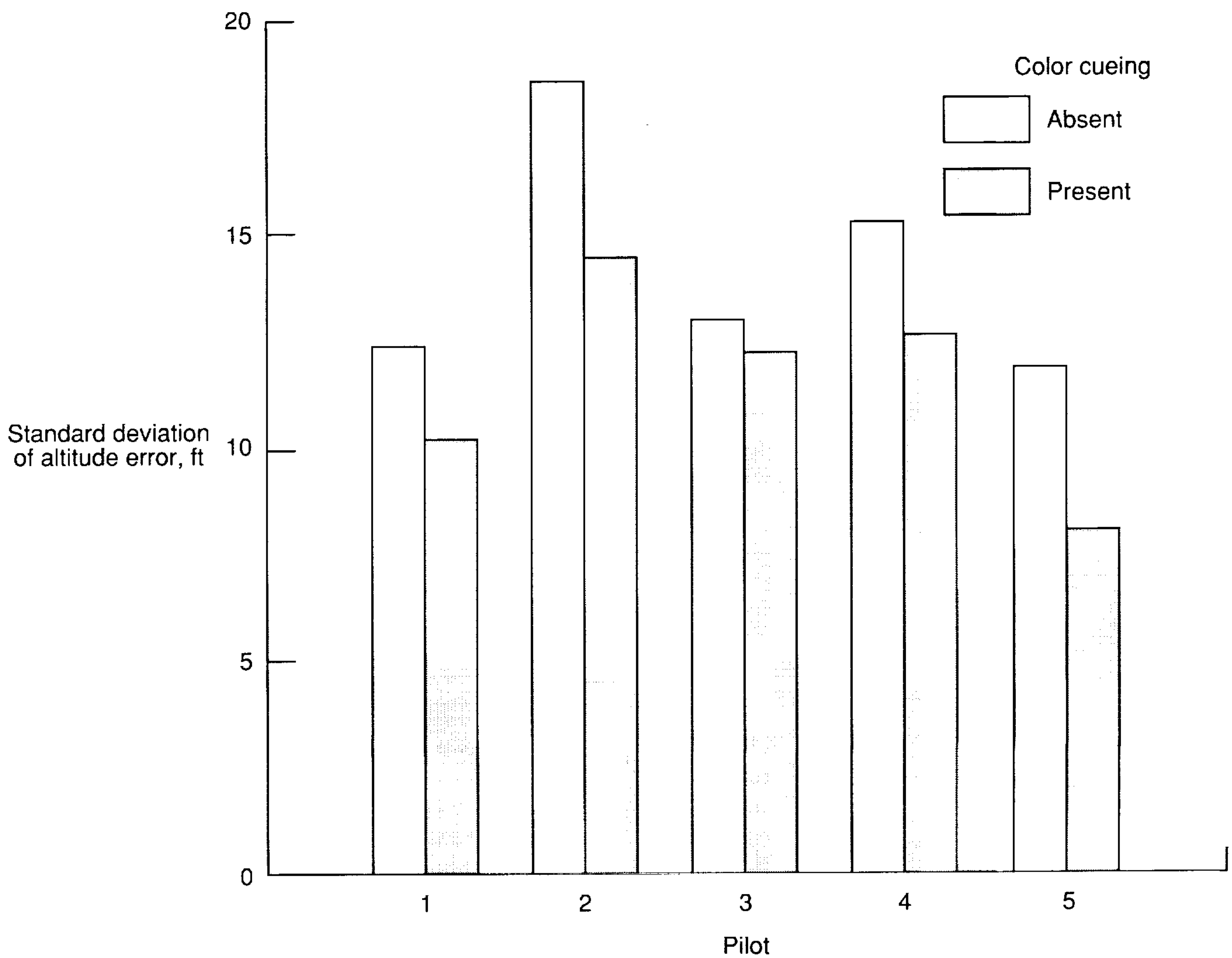



Figure 25. Effect of color cueing in monitoring task display on standard deviation of altitude error for nonstereo tracking task pathway display condition for each pilot.

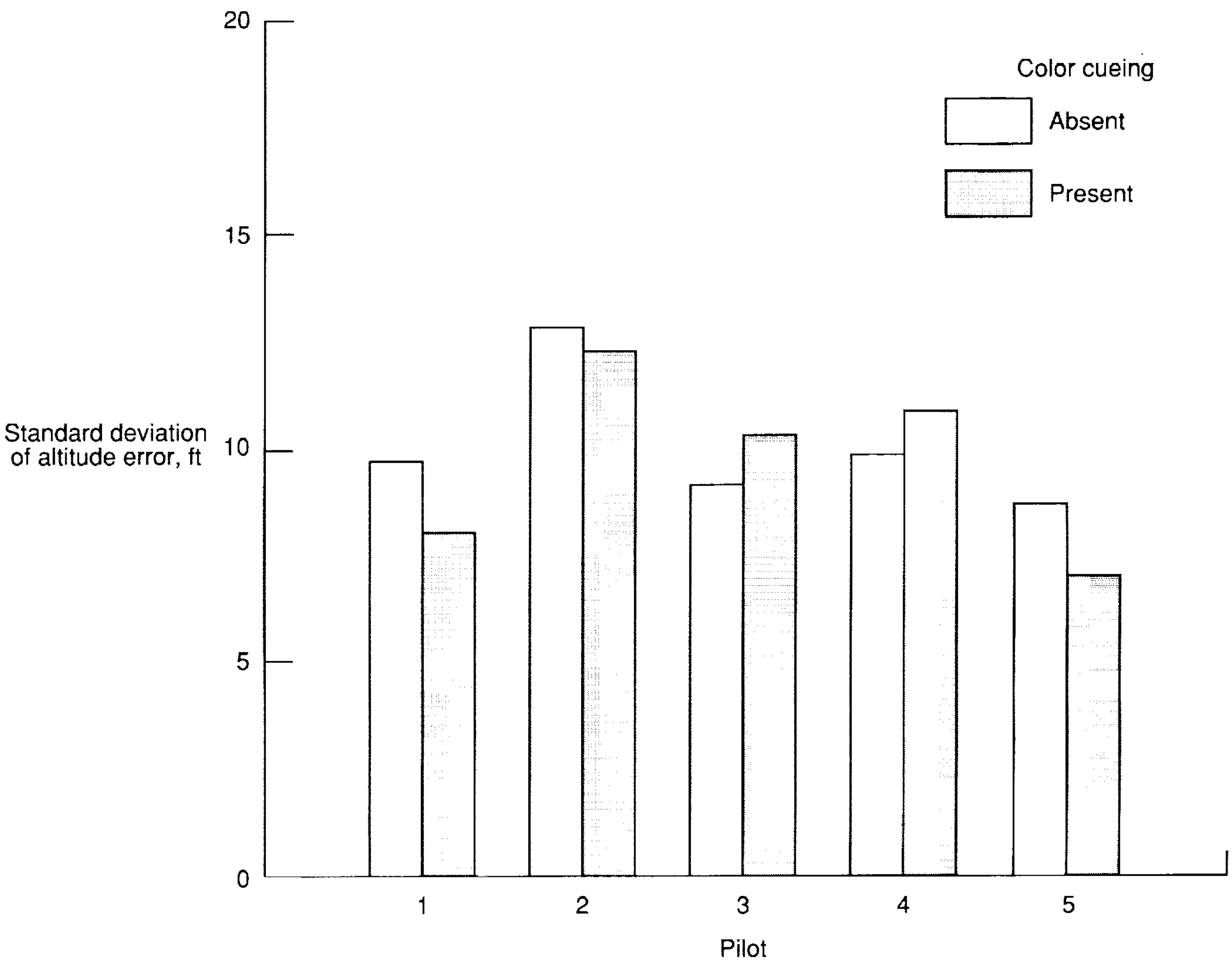



Figure 26. Effect of color cueing in monitoring task display on standard deviation of altitude error for stereo tracking task pathway display condition for each pilot.

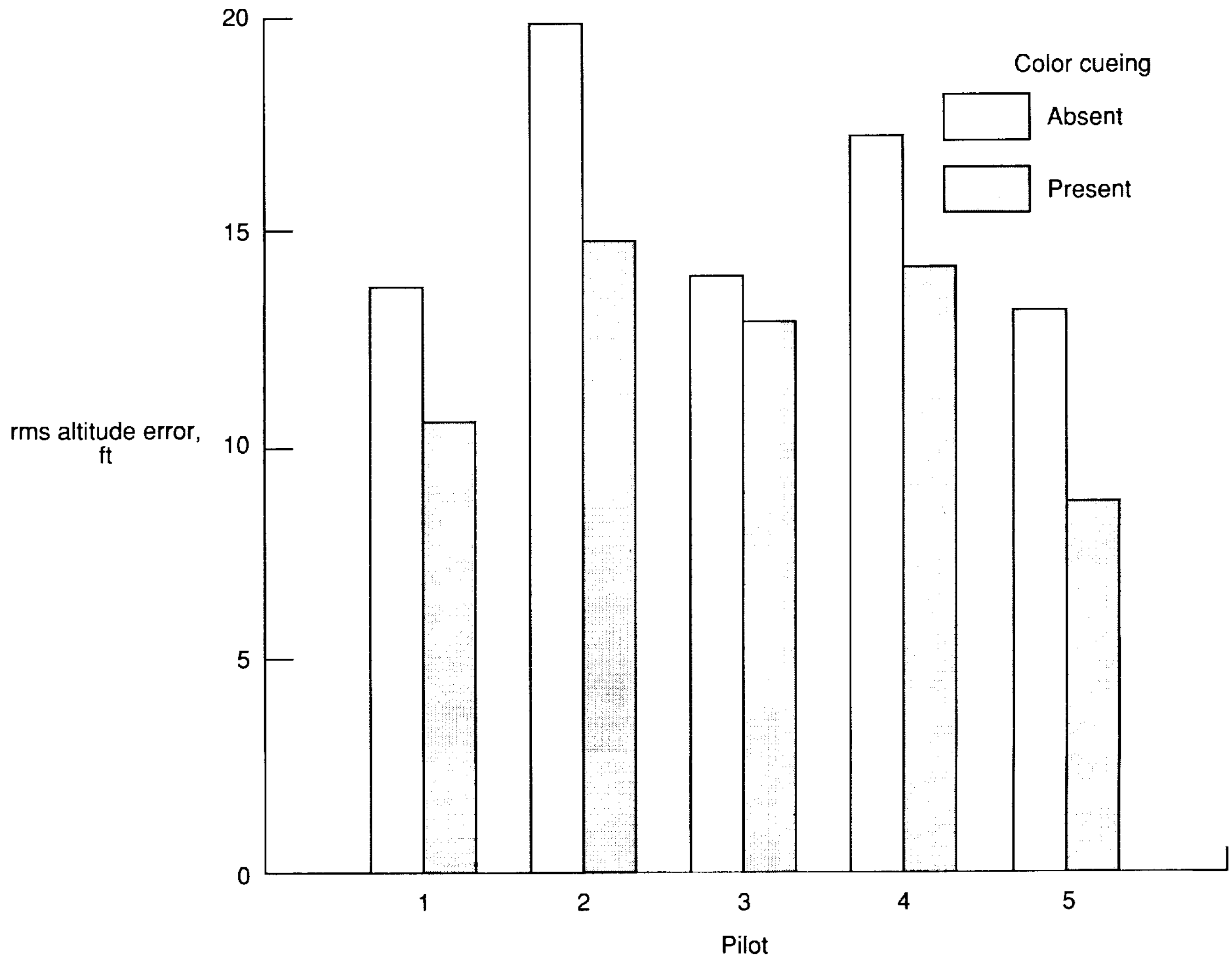



Figure 27. Effect of color cueing in monitoring task display on rms altitude error for nonstereo tracking task pathway display condition for each pilot.

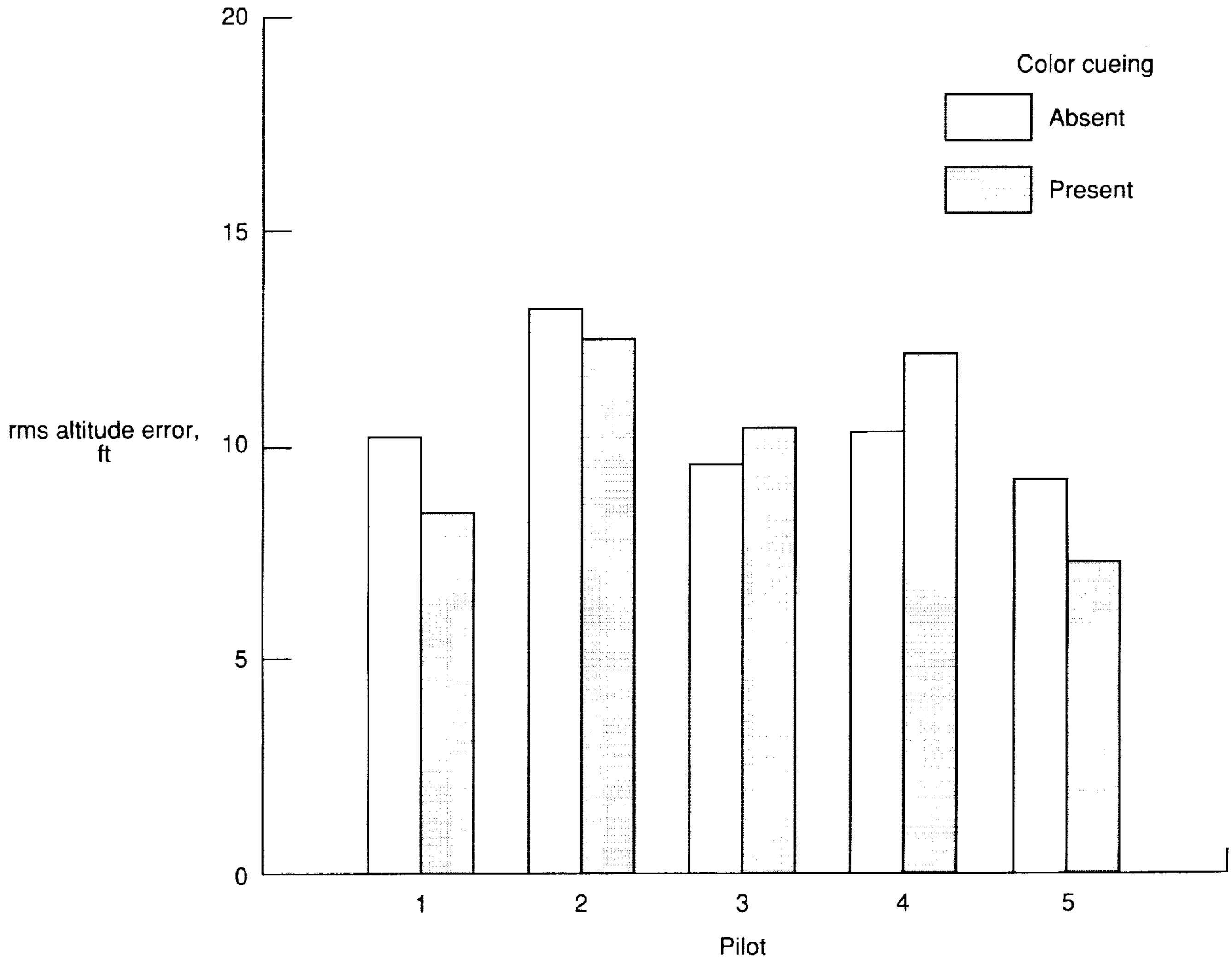



Figure 28. Effect of color cueing in monitoring task display on rms altitude error for stereo tracking task pathway display condition for each pilot.

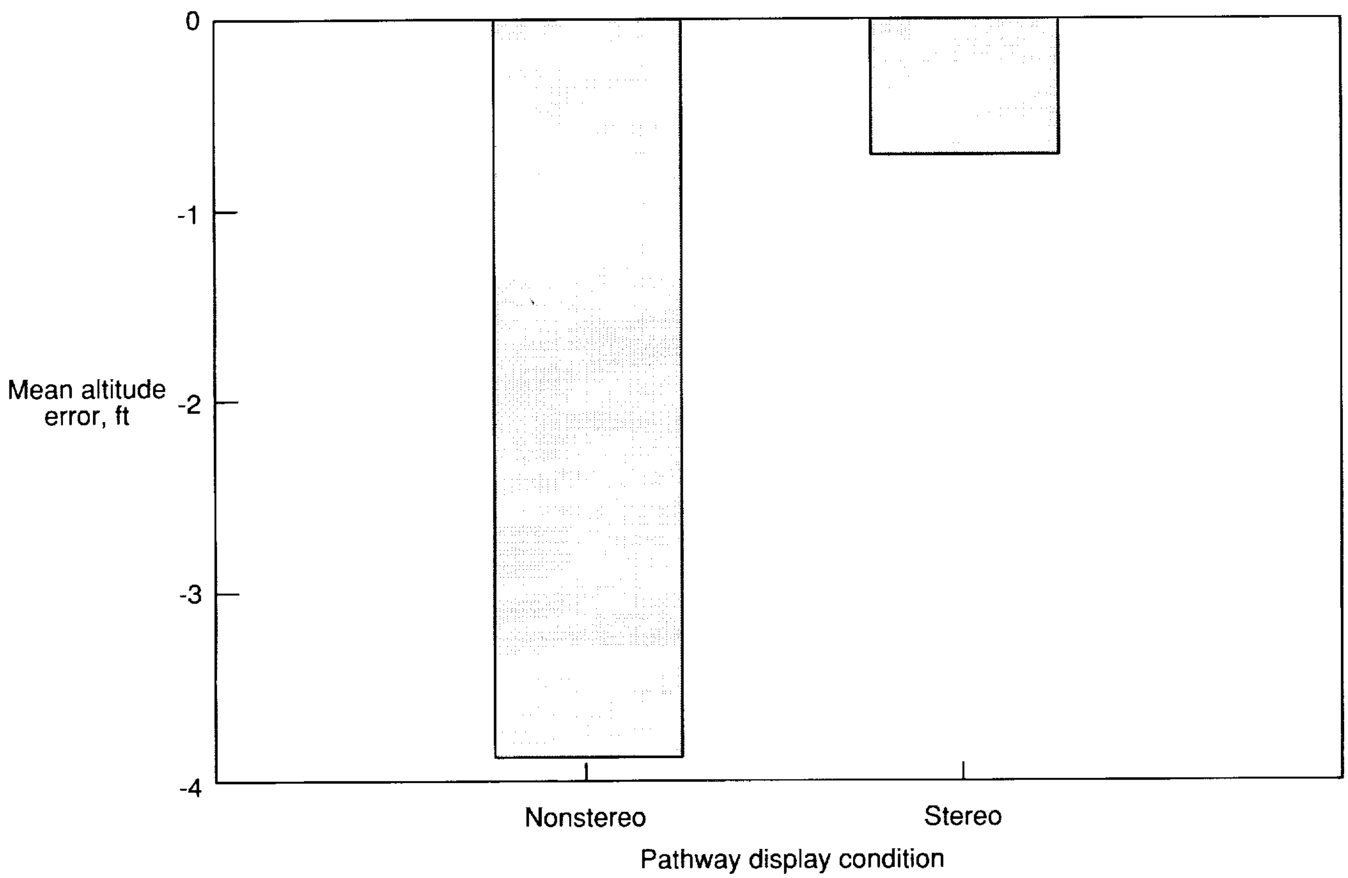



Figure 29. Effect of tracking task pathway display condition on mean altitude error for tracking task for all pilots.

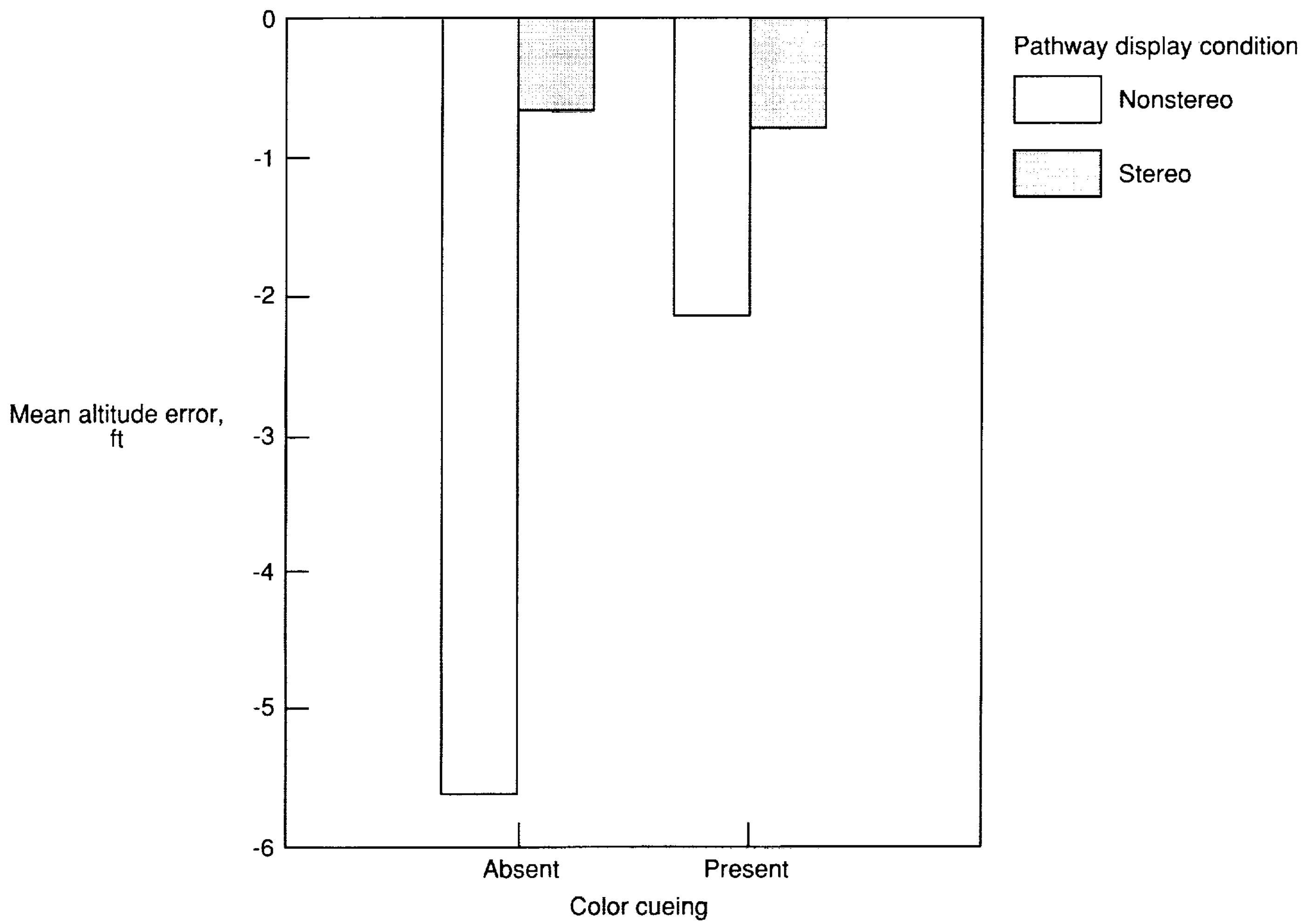



Figure 30. Effect of tracking task pathway display condition on mean altitude error for tracking task across color cueing in monitoring task display for all pilots.

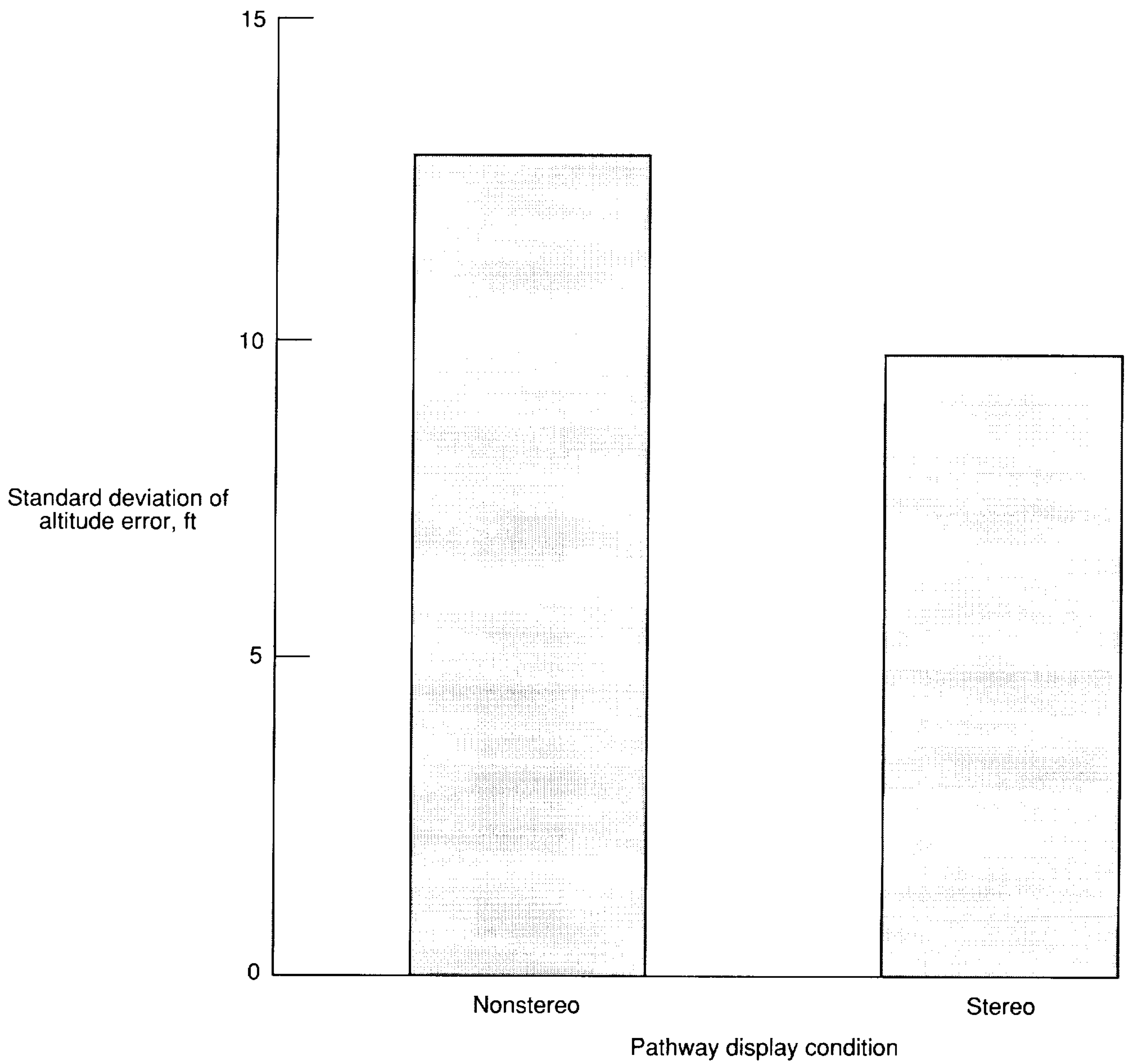



Figure 31. Effect of tracking task pathway display condition on standard deviation of altitude error for tracking task for all pilots.

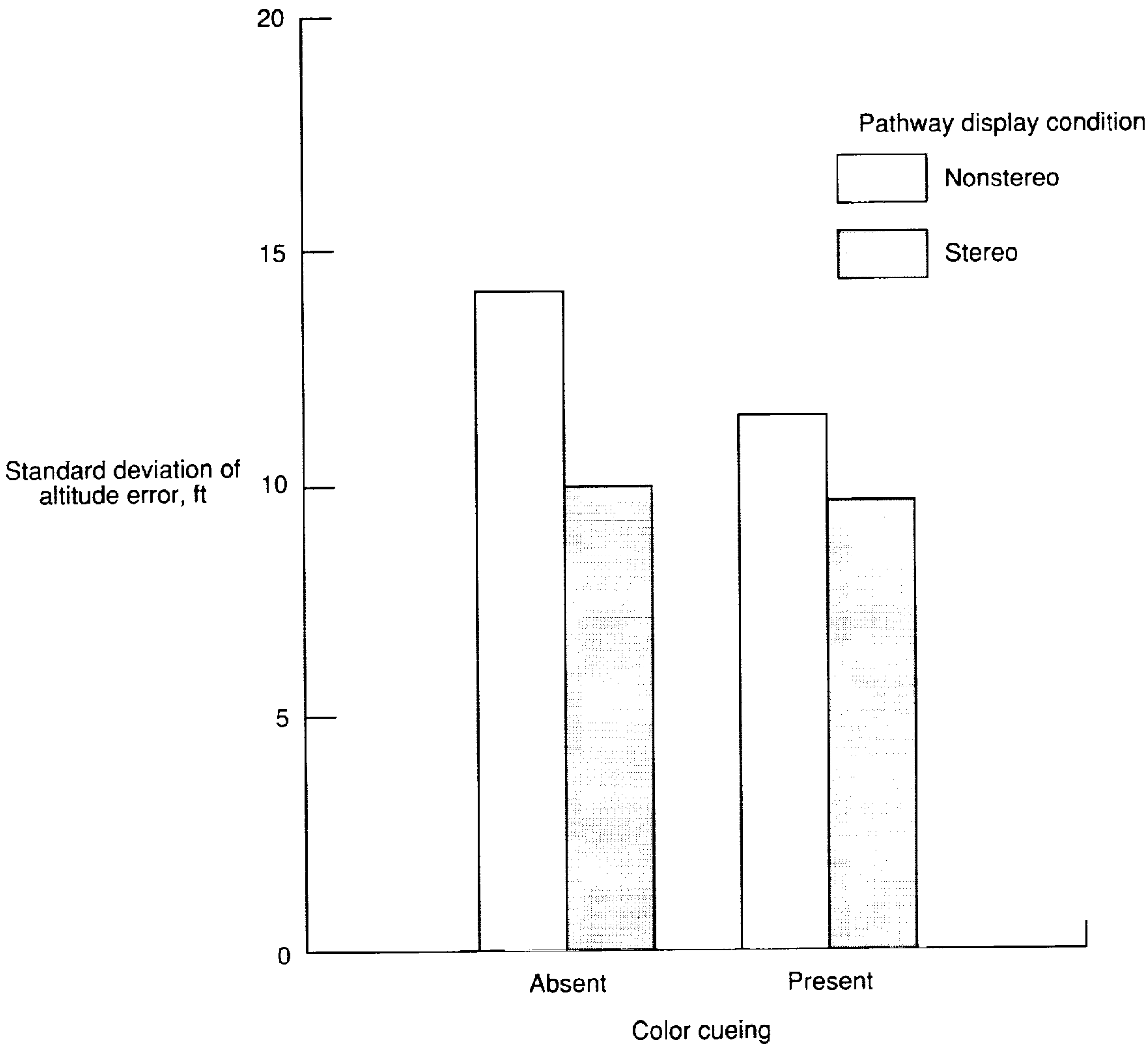



Figure 32. Effect of tracking task pathway display condition on altitude error standard deviation for tracking task across color cueing in monitoring task display for all pilots.

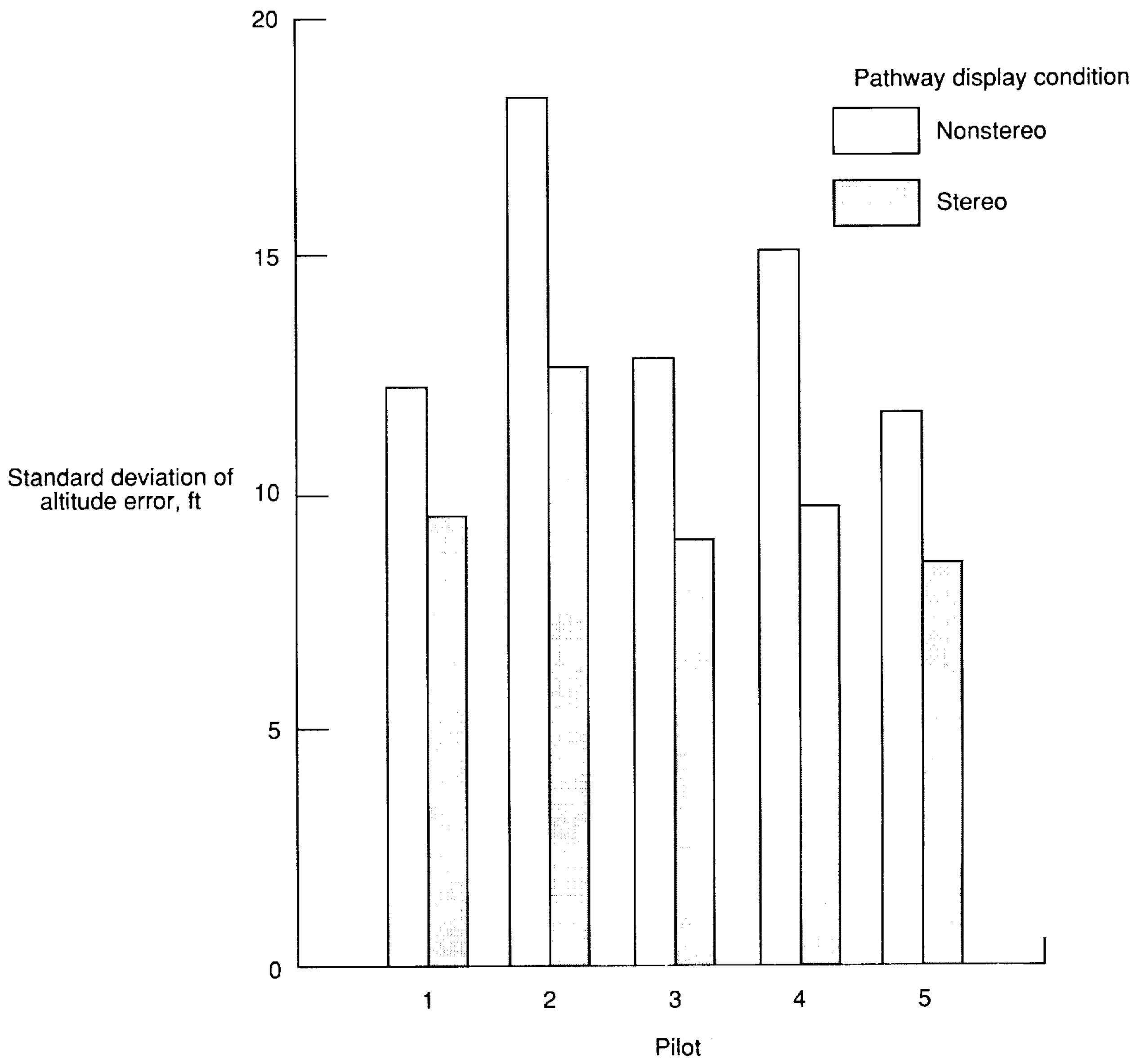



Figure 33. Effect of tracking task pathway display condition on standard deviation of altitude error for color cueing absent in monitoring task display for each pilot.

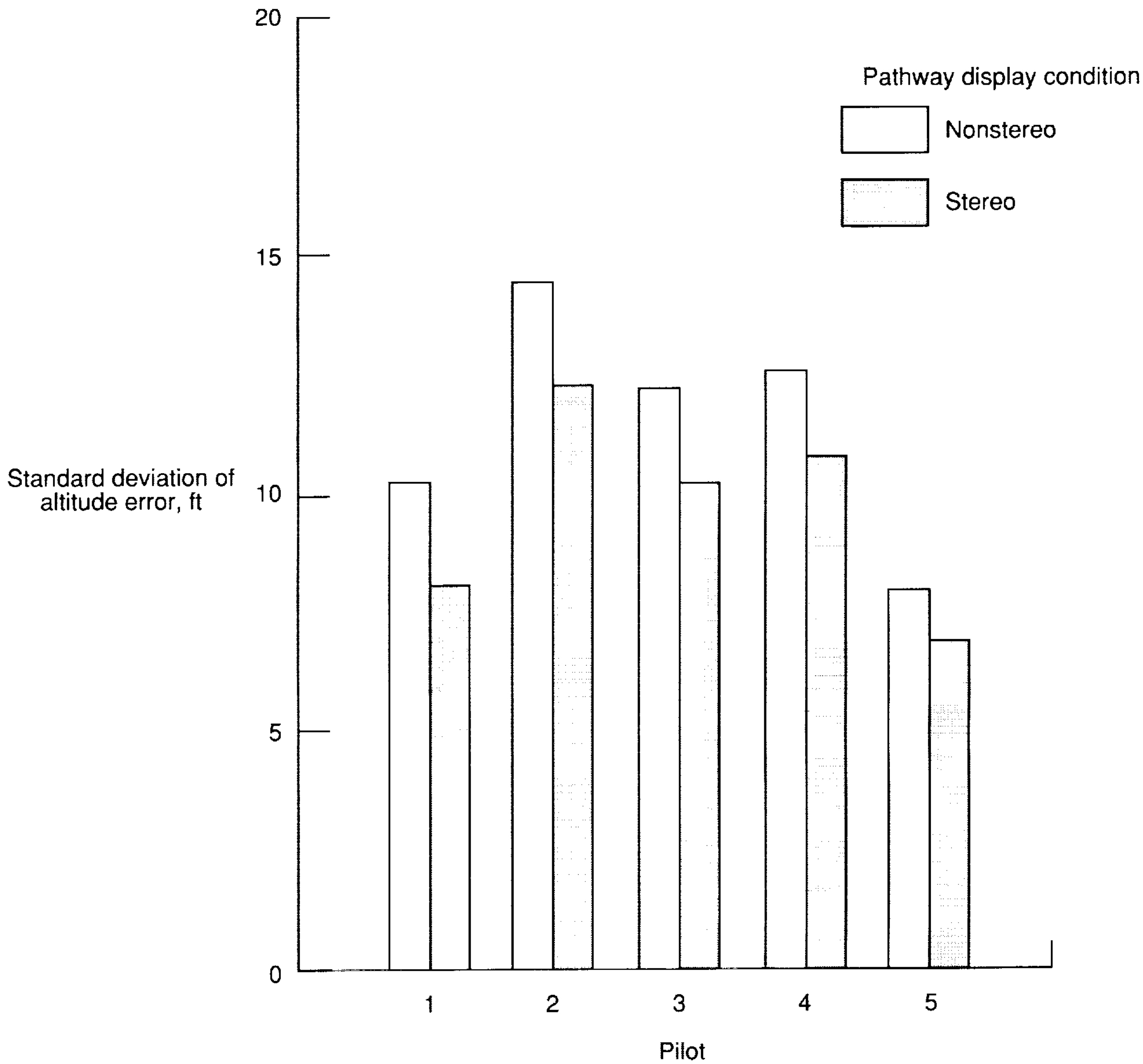



Figure 34. Effect of tracking task pathway display condition on standard deviation of altitude error for color cueing present in monitoring task display for each pilot.

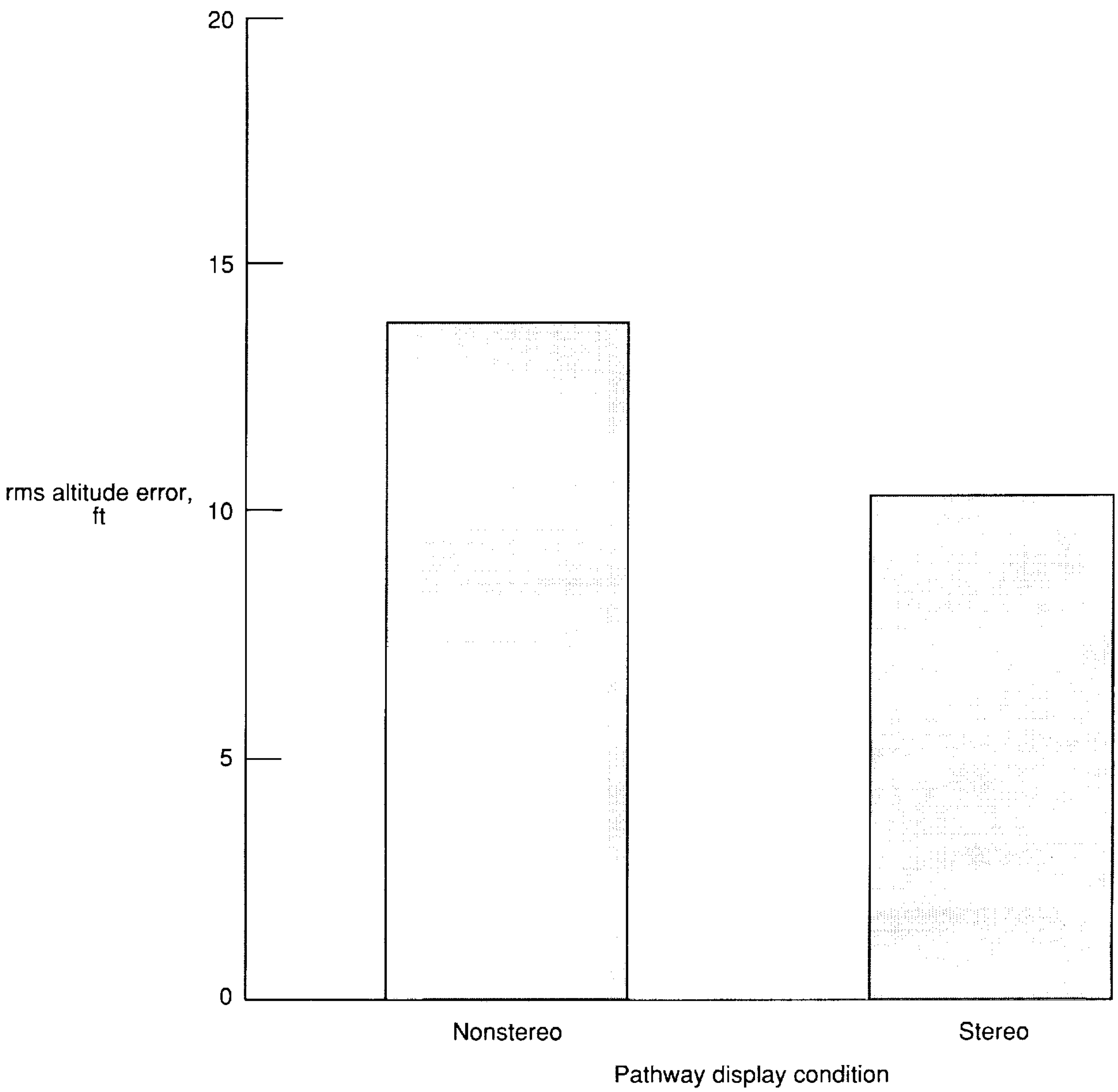



Figure 35. Effect of tracking task pathway display condition on rms altitude error for tracking task for all pilots.

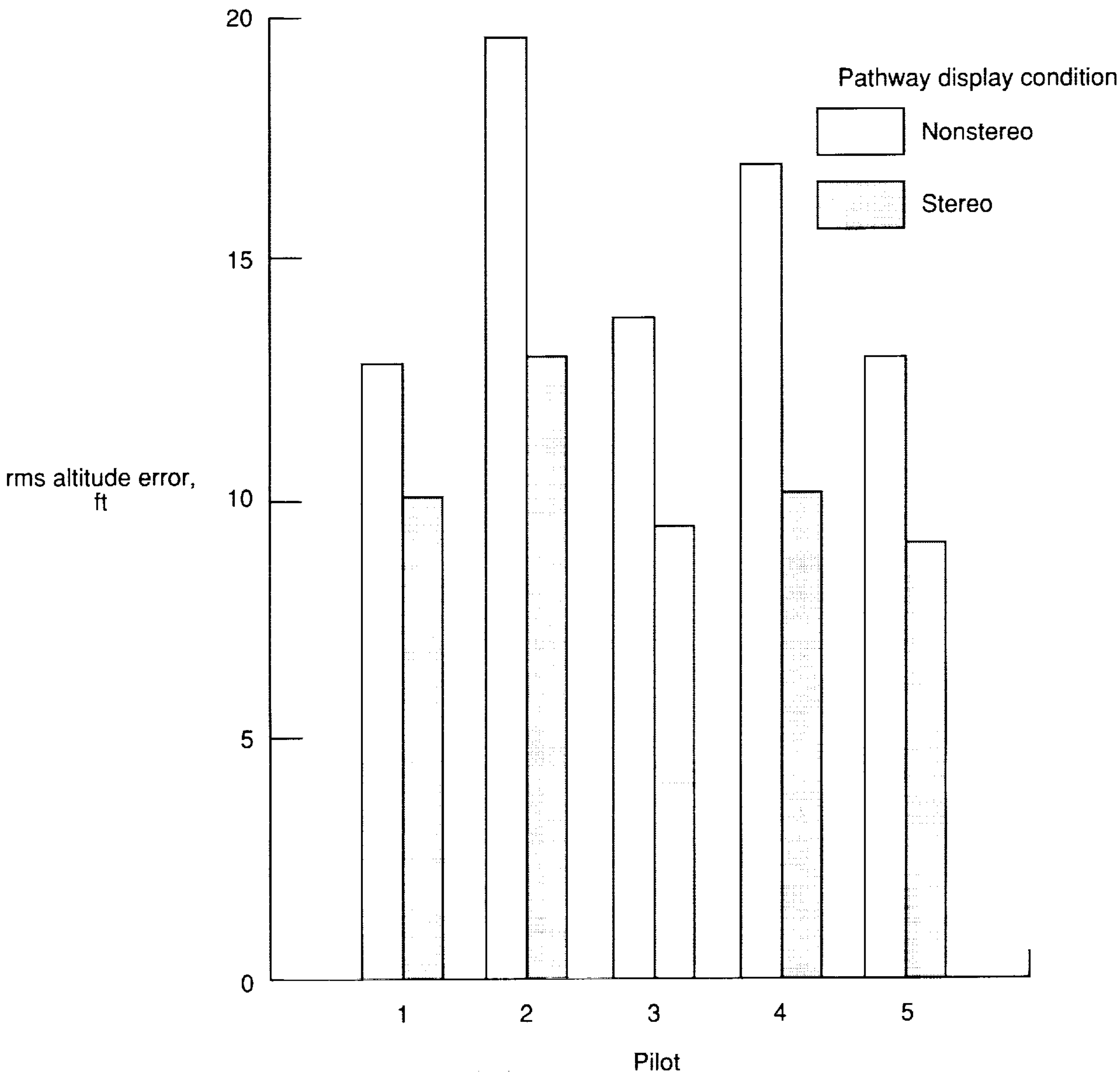



Figure 36. Effect of tracking task pathway display condition on rms altitude error for color cueing absent in monitoring task display for each pilot.

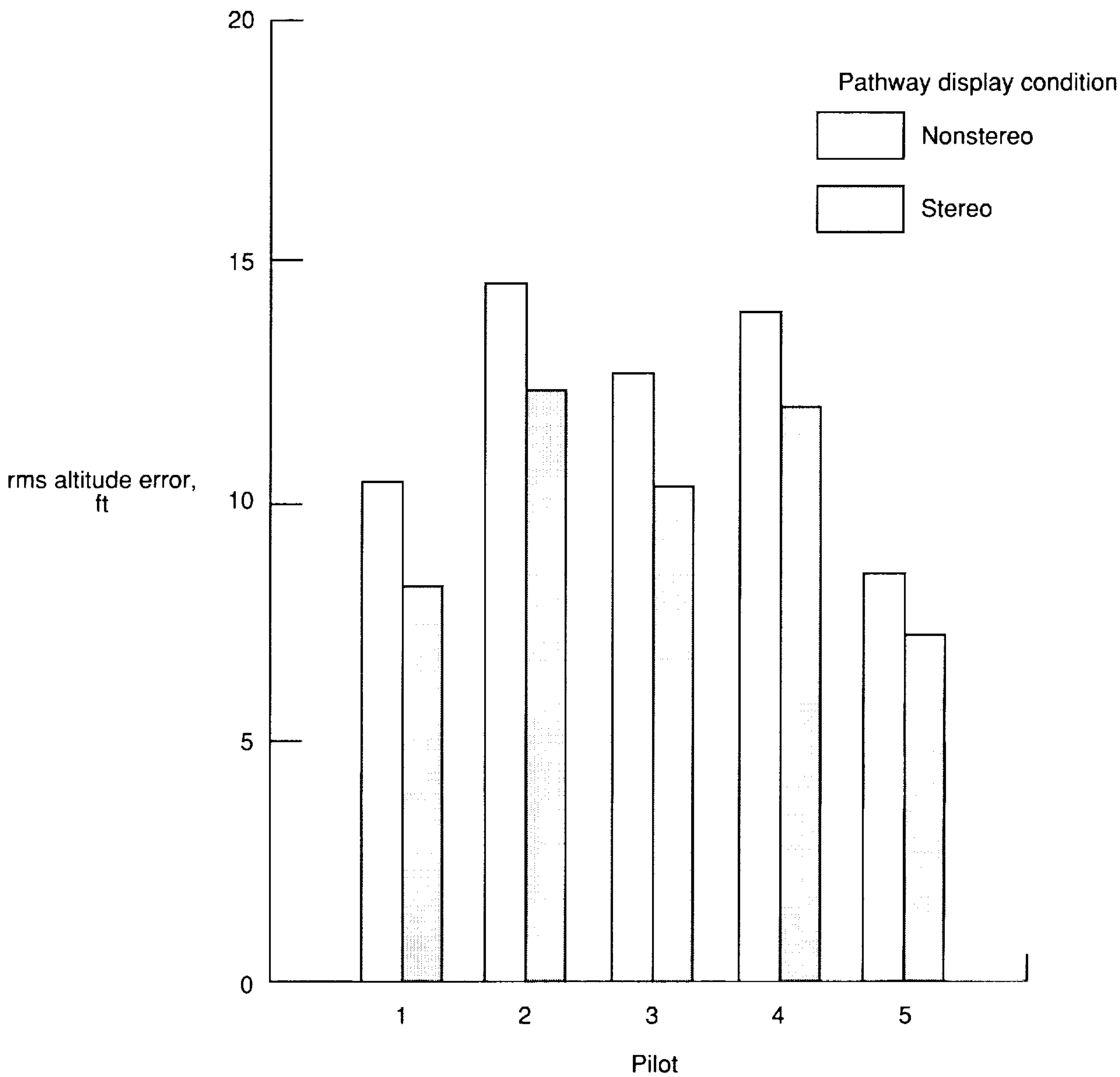



Figure 37. Effect of tracking task pathway display condition on rms altitude error for color cueing present in monitoring task display for each pilot.

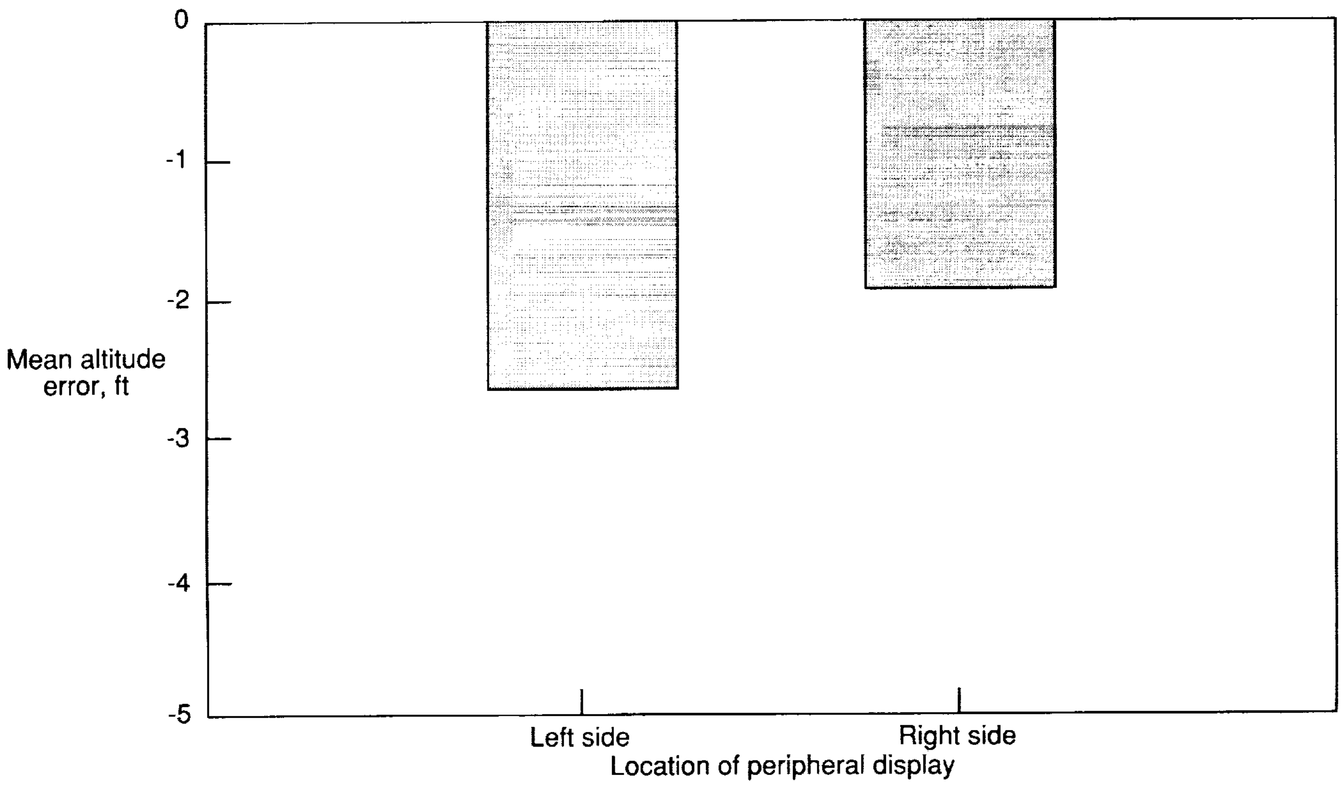



Figure 38. Effect of location of peripheral area display for monitoring task on mean altitude error for tracking task for all pilots.

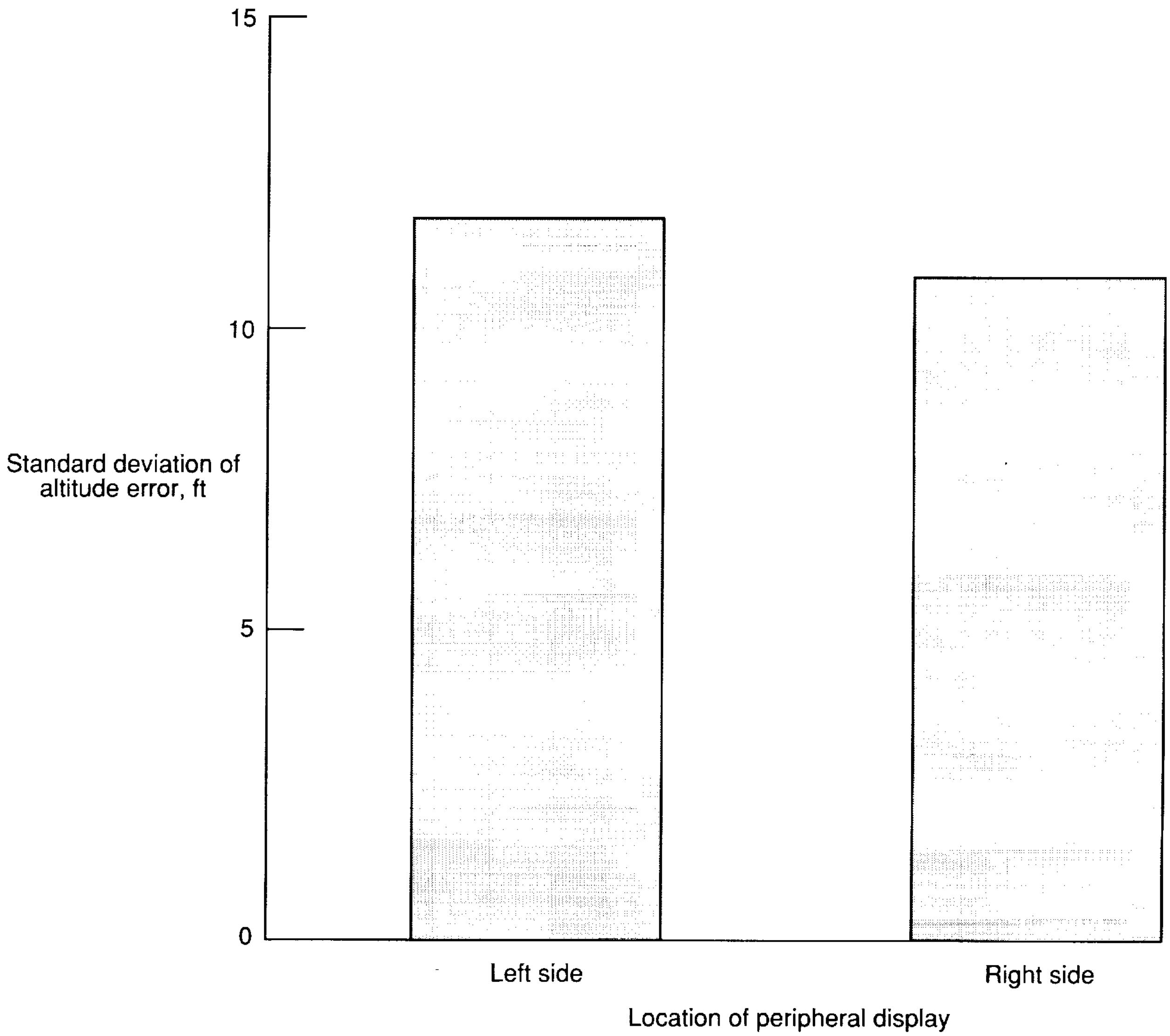



Figure 39. Effect of location of peripheral area display for monitoring task on standard deviation of altitude error for tracking task for all pilots.

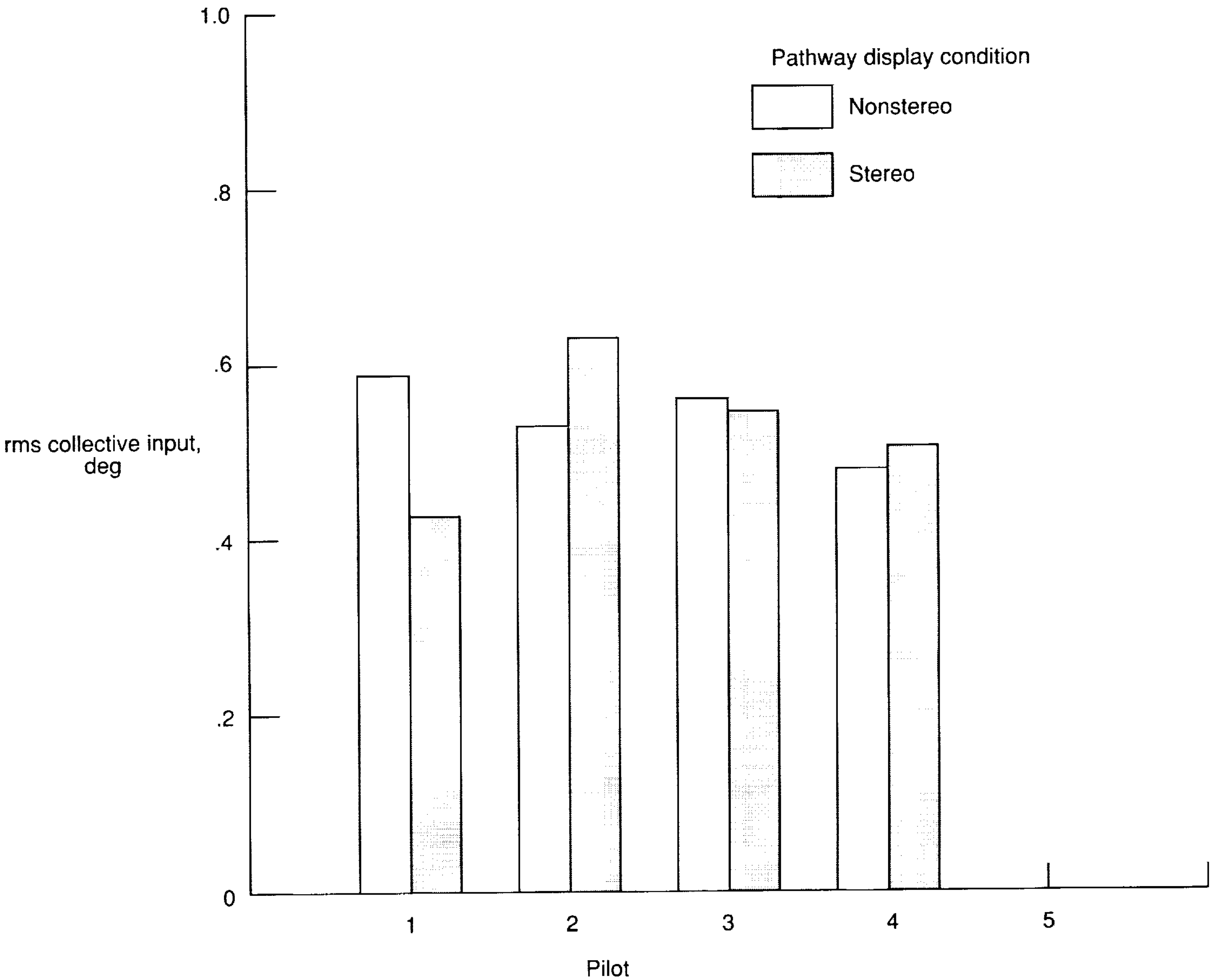



Figure 40. Effect of color cueing in monitoring task display on rms collective input for tracking task for each pilot.

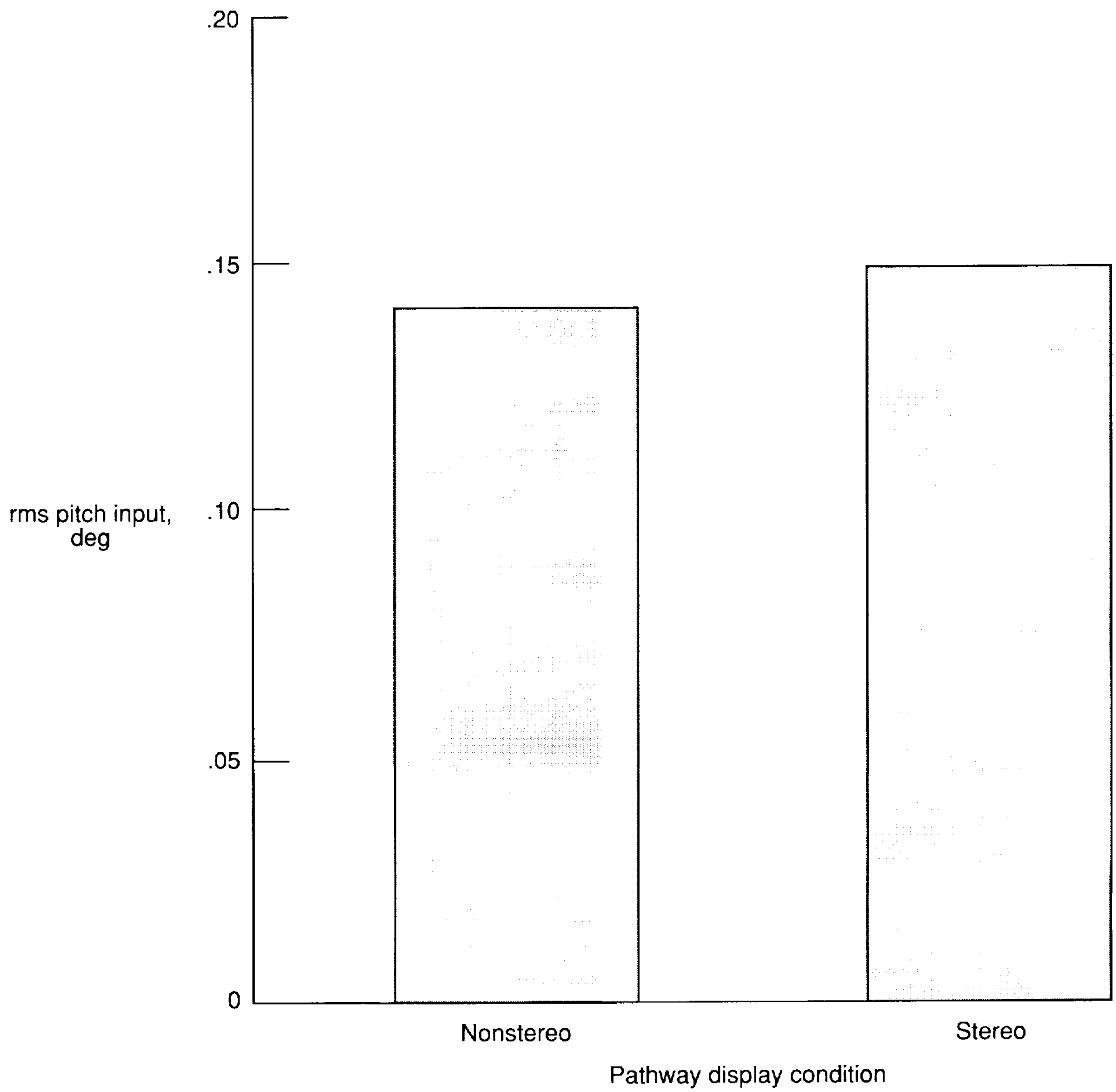



Figure 41. Effect of tracking task pathway display condition on rms pitch input for tracking task for all pilots.

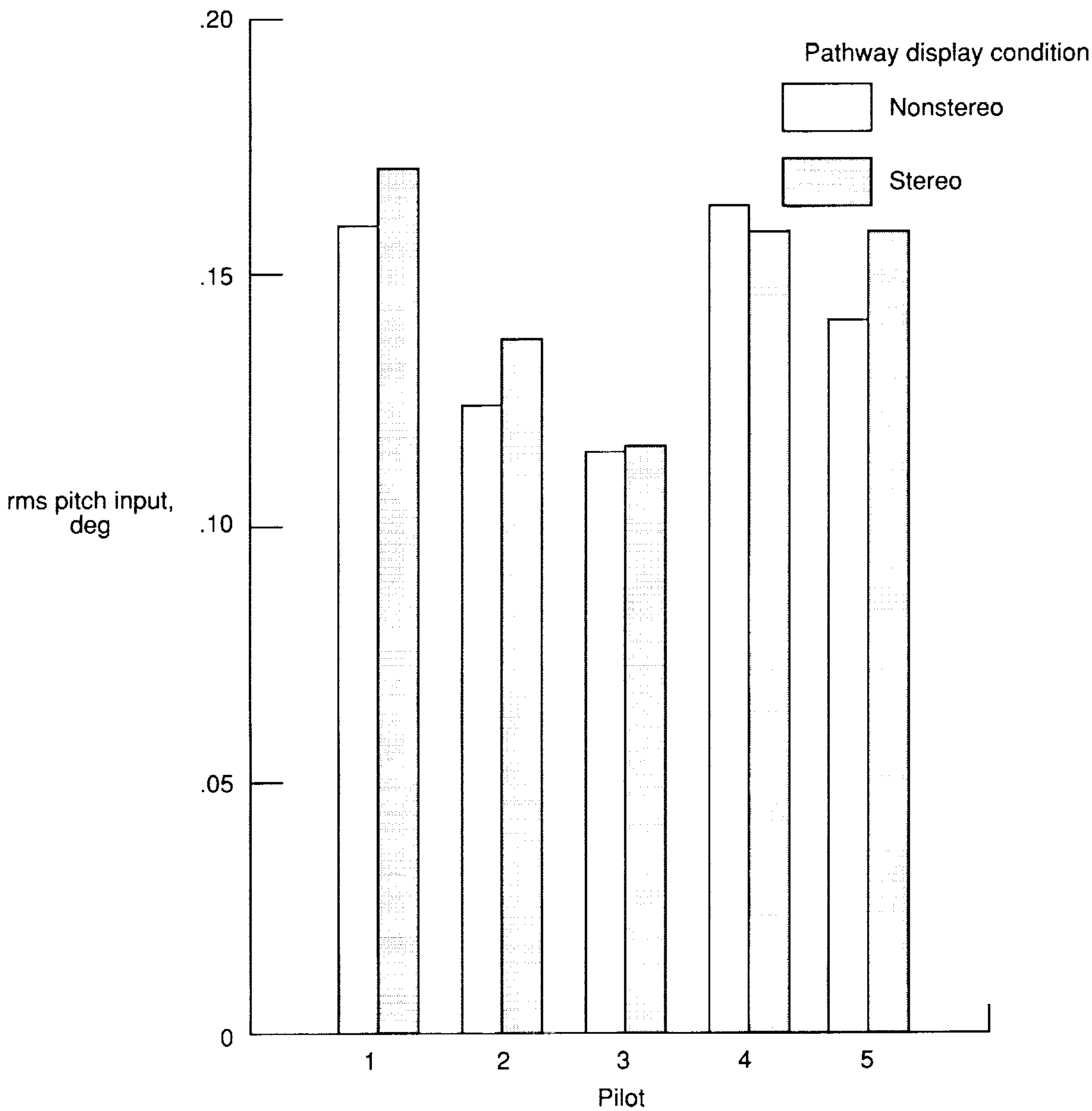



Figure 42. Effect of tracking task pathway display condition on rms pitch input for tracking task for each pilot.

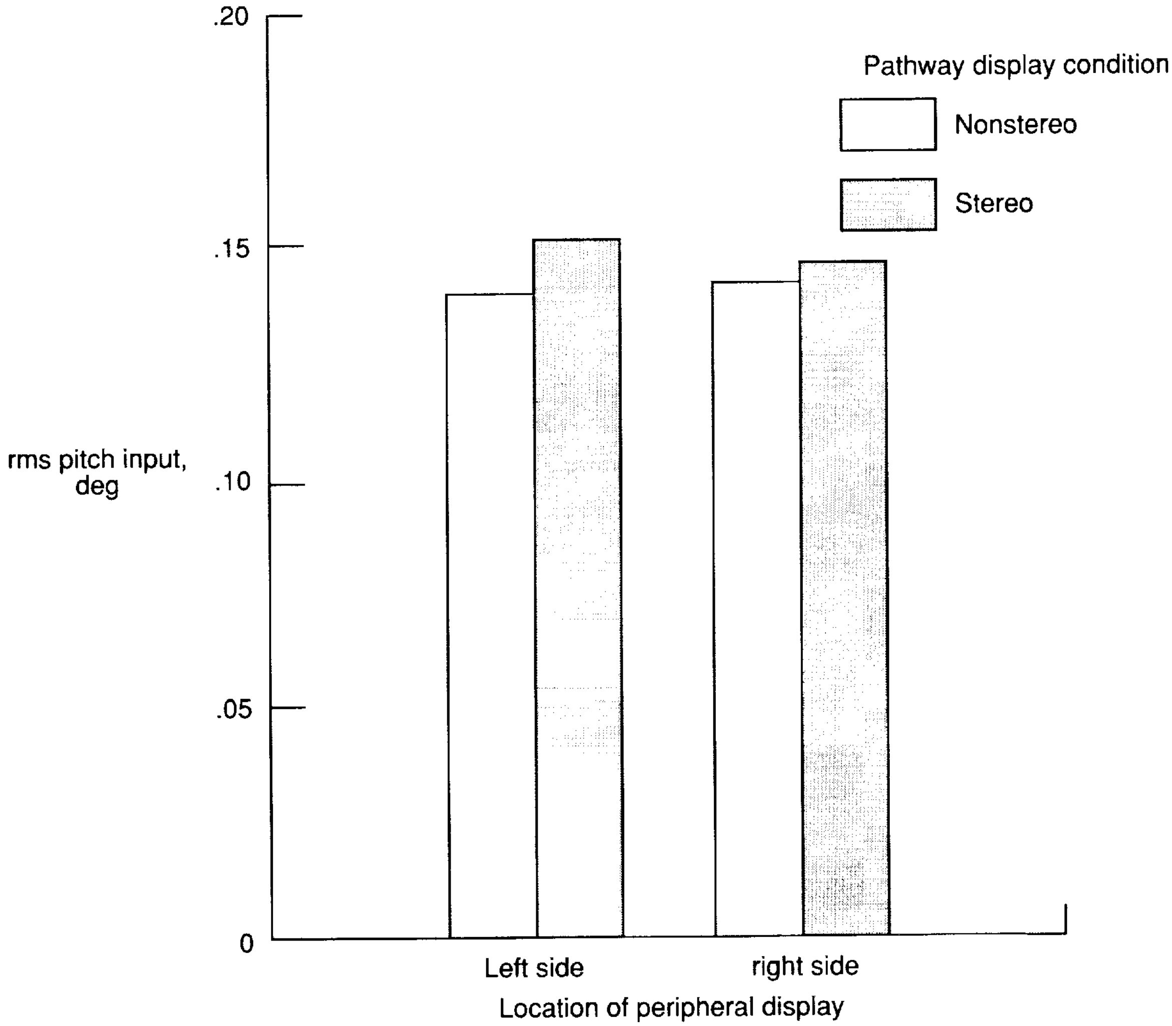



Figure 43. Effect of location of peripheral area display for monitoring task display on rms pitch input across tracking task pathway display condition for all pilots.

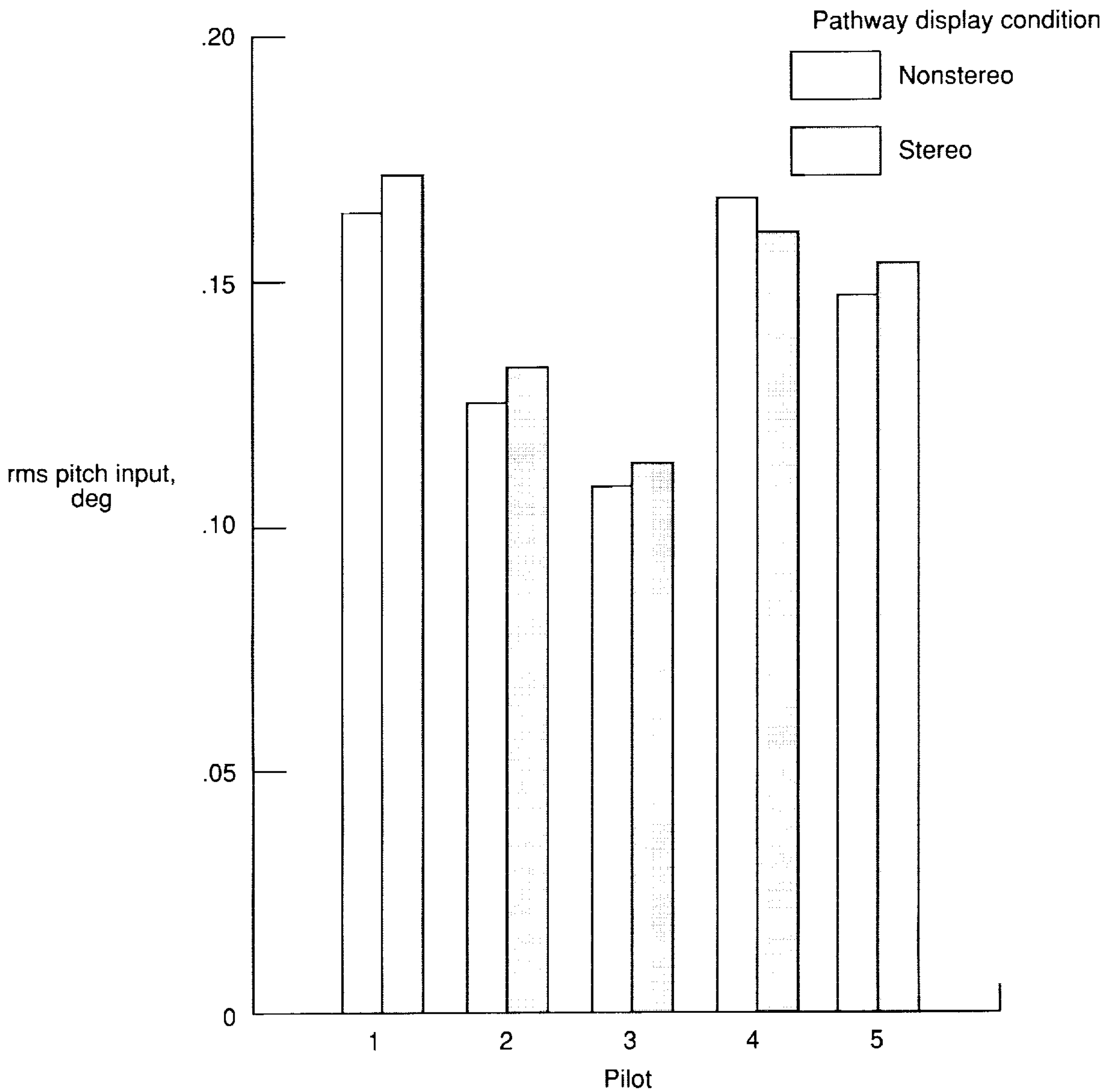



Figure 44. Effect of tracking task pathway display condition on rms pitch input with monitoring task peripheral area display at right-side location for each pilot.

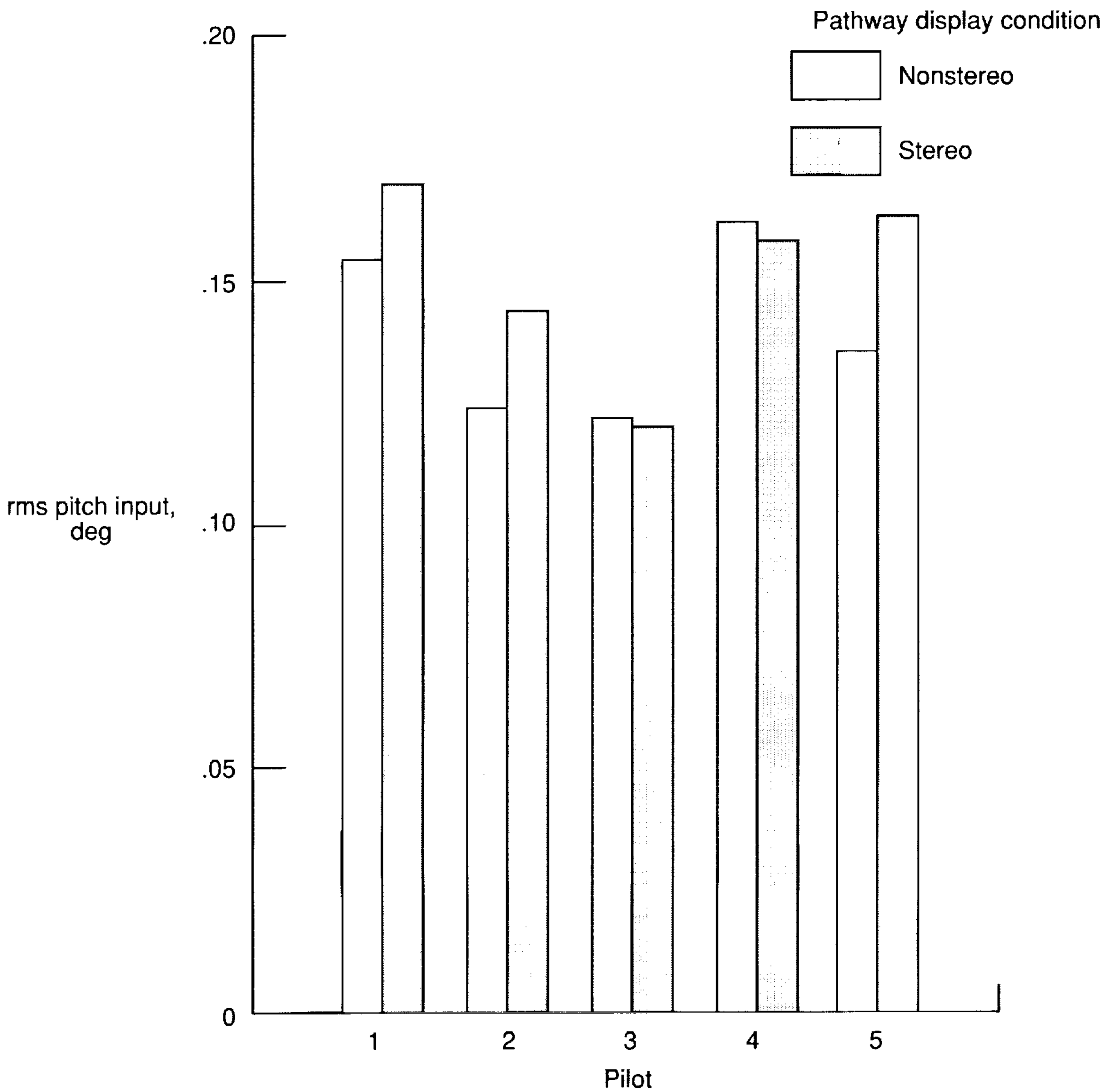



Figure 45. Effect of tracking task pathway display condition on rms pitch input with monitoring task peripheral area display at left-side location for each pilot.

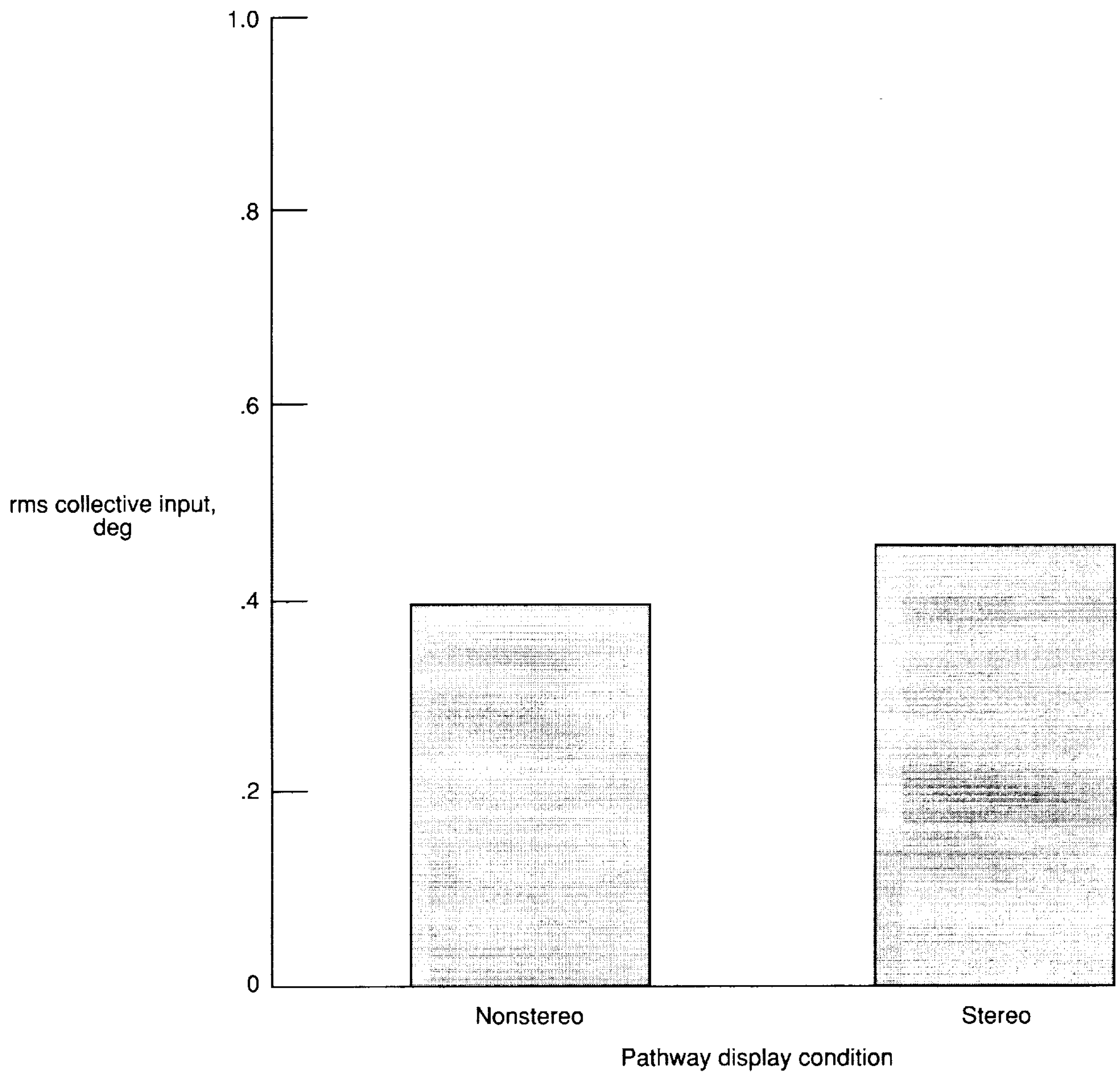



Figure 46. Effect of tracking task pathway display condition on rms collective input for tracking task for all pilots.

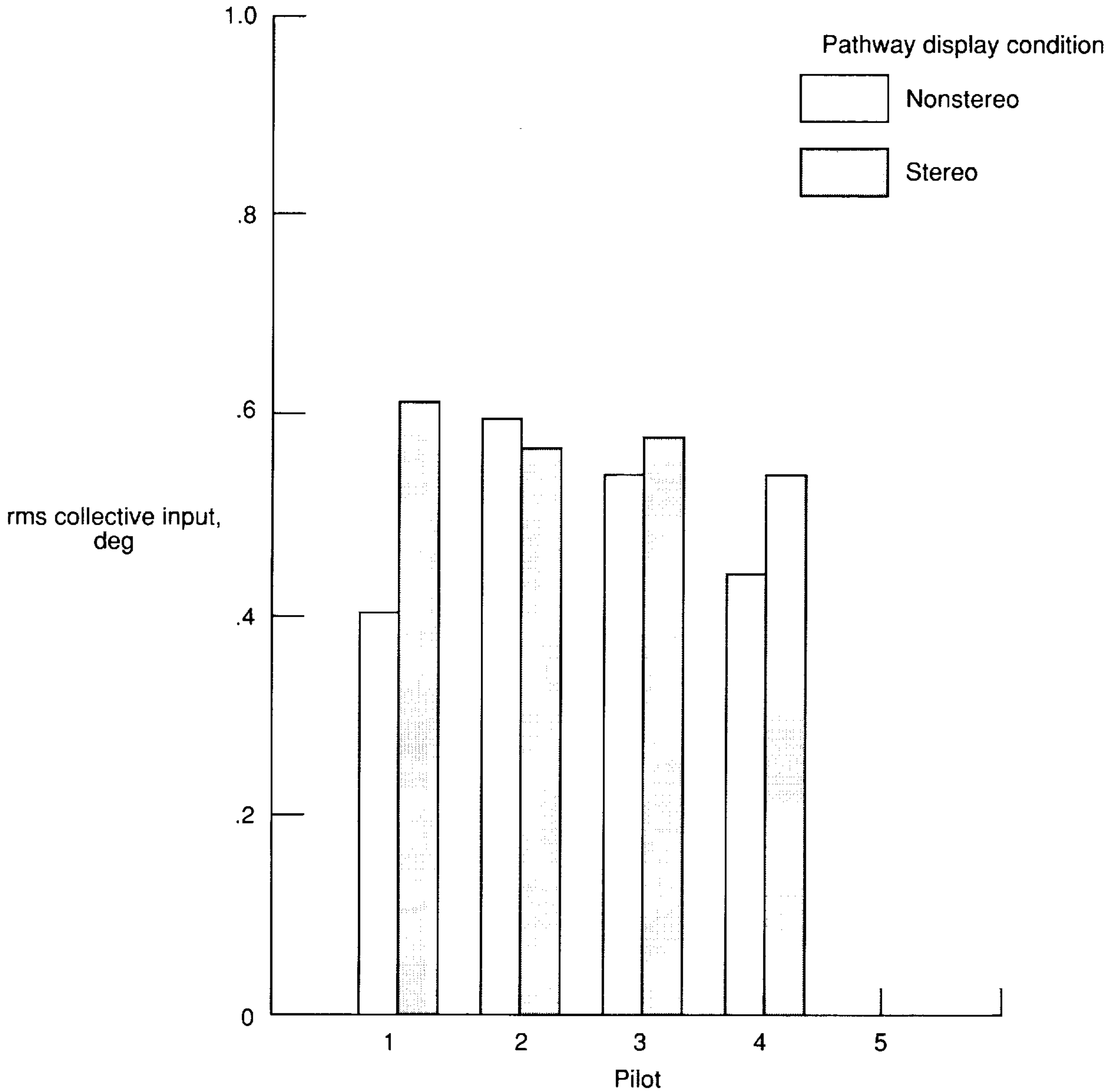



Figure 47. Effect of tracking task pathway display condition on rms collective input for tracking task for each pilot.

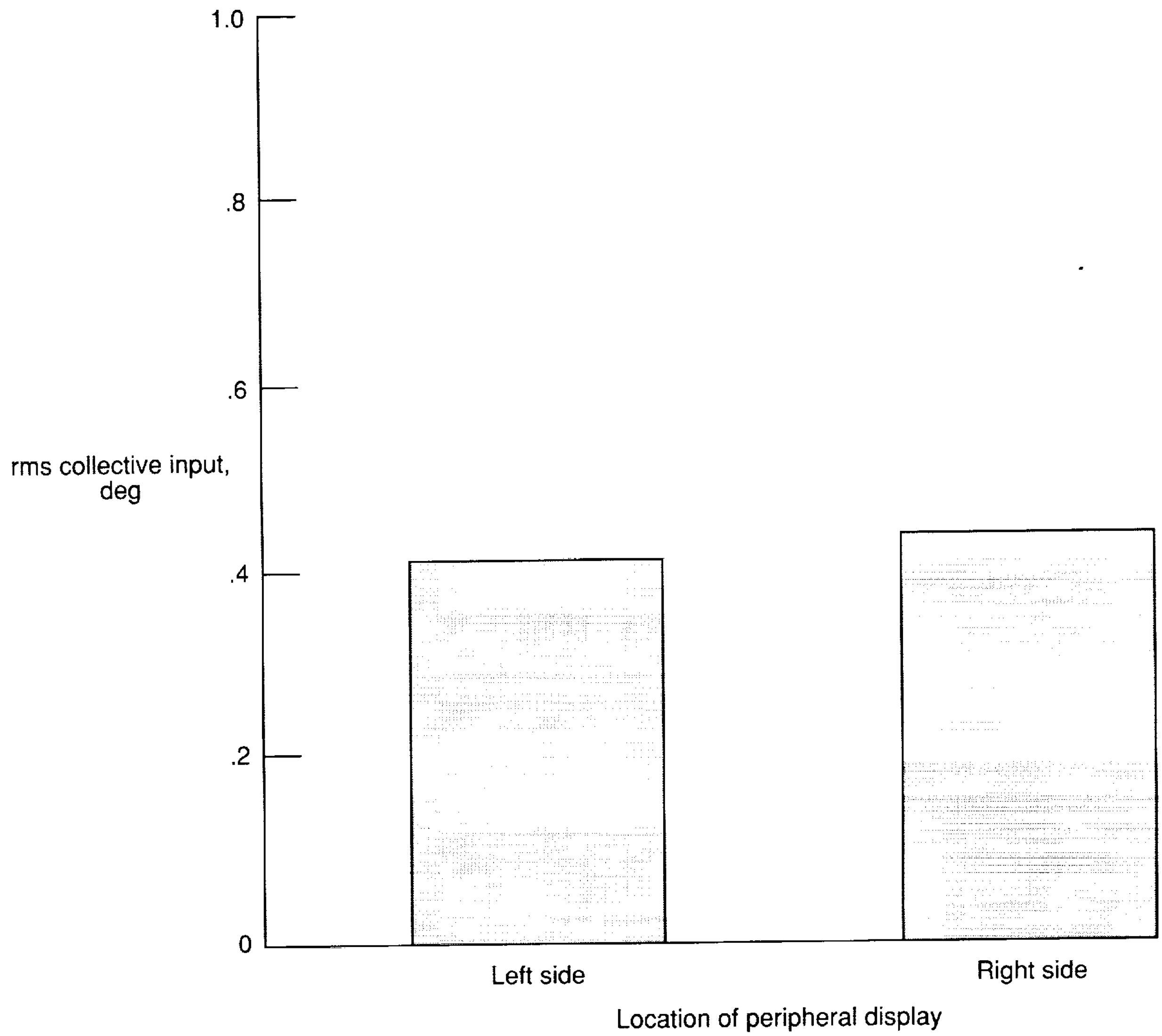



Figure 48. Effect of location of peripheral area display for monitoring task on rms collective input for tracking task for all pilots.

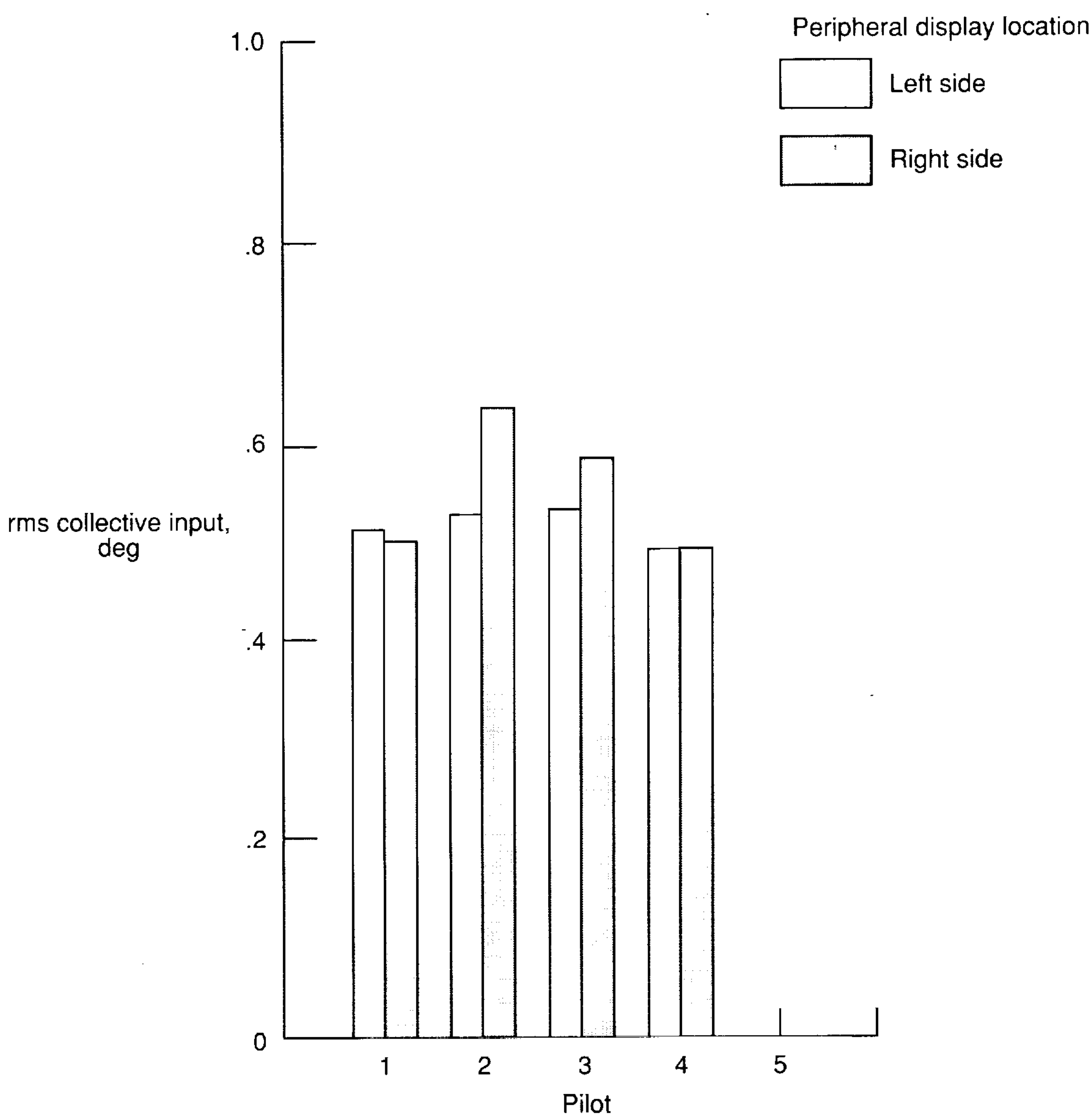



Figure 49. Effect of location of peripheral area display for monitoring task on rms collective input for tracking task for each pilot.

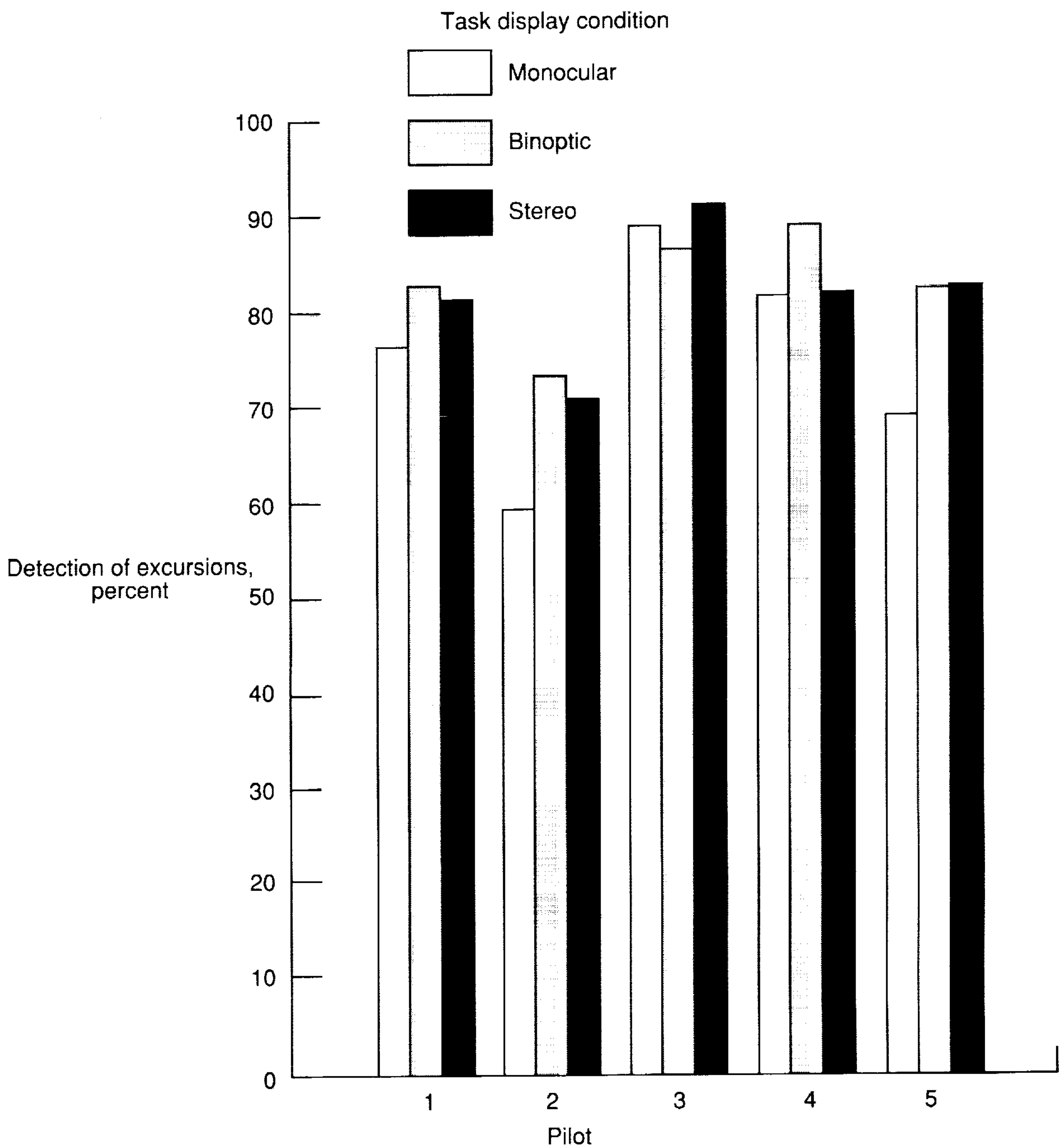



Figure 50. Effect of monitoring task display condition on detection of boundary excursions for monitoring task for each pilot.

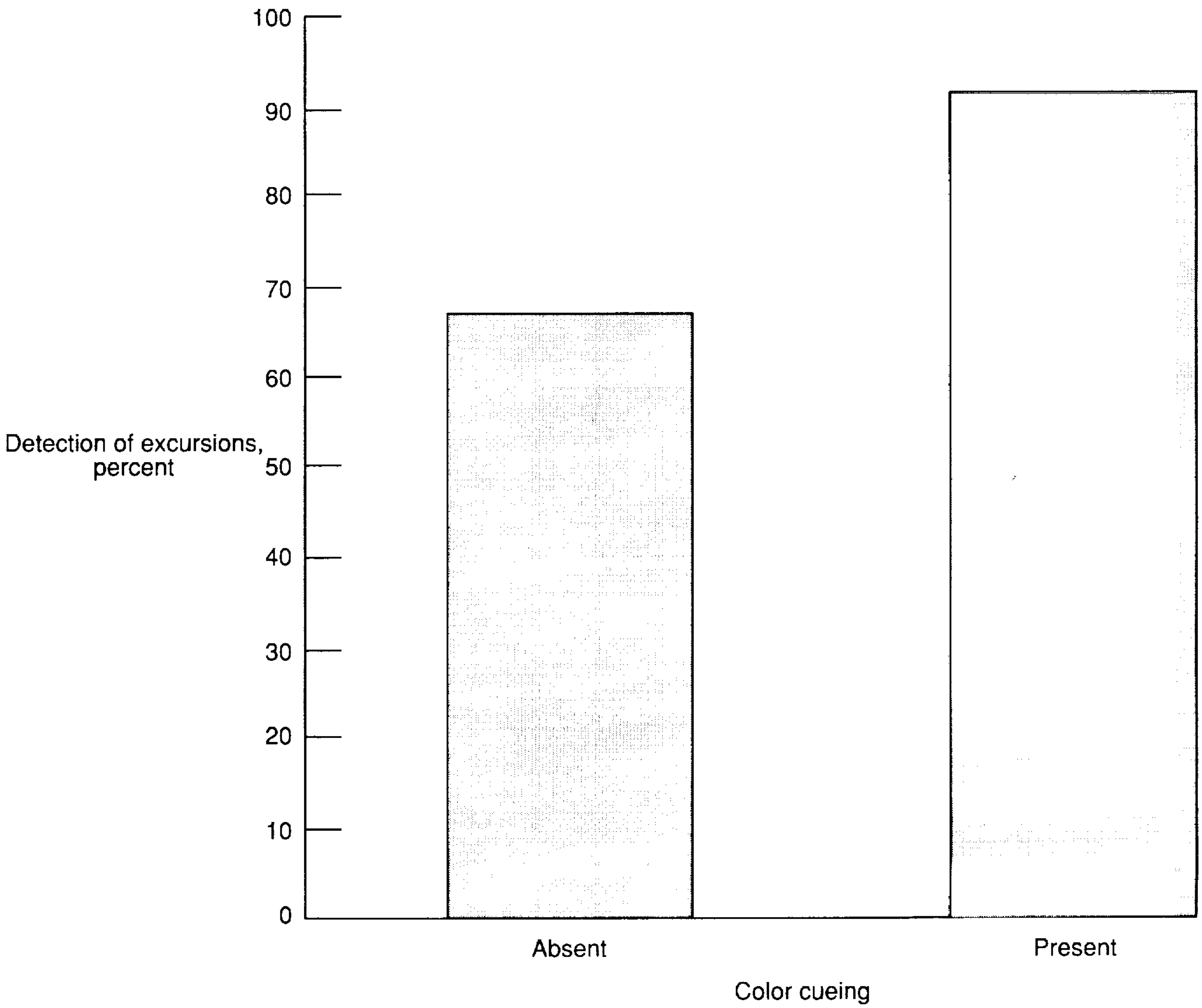



Figure 51. Effect of color cueing in monitoring task display on detection of excursions for monitoring task for all pilots.

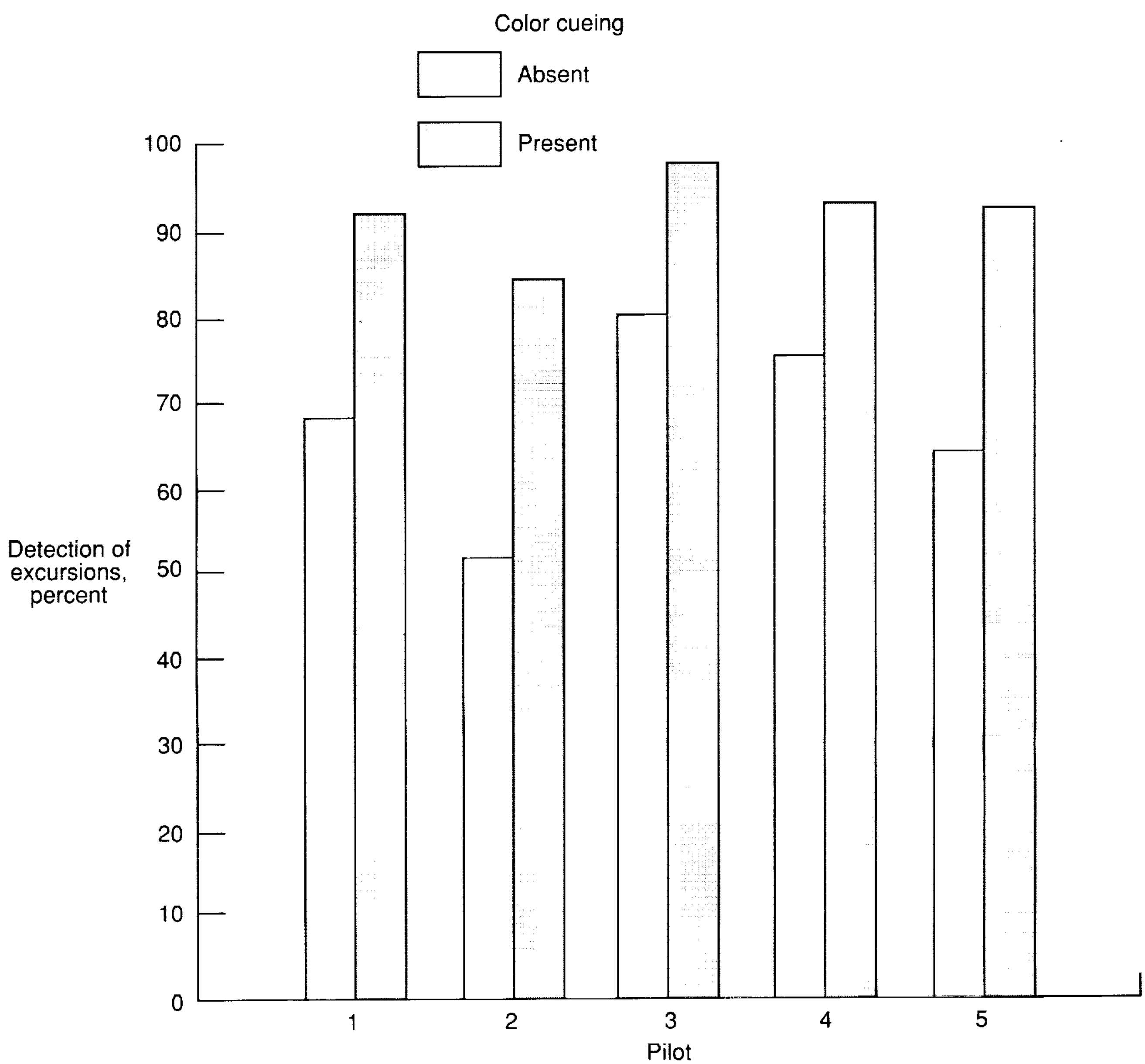



Figure 52. Effect of color cueing in monitoring task display on detection of excursions for monitoring task for each pilot.

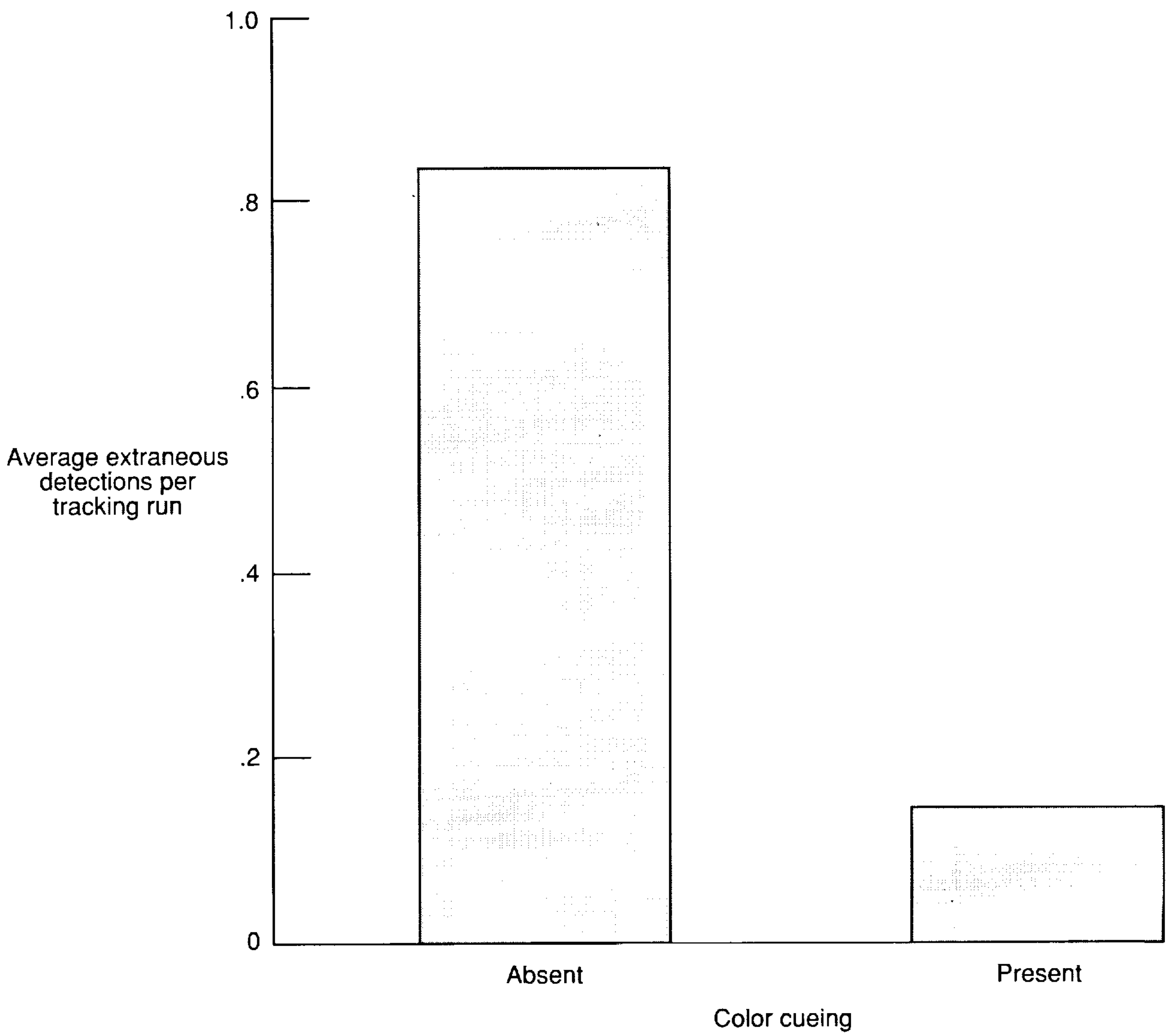



Figure 53. Effect of color cueing in monitoring task display on extraneous detections for monitoring task for all pilots.

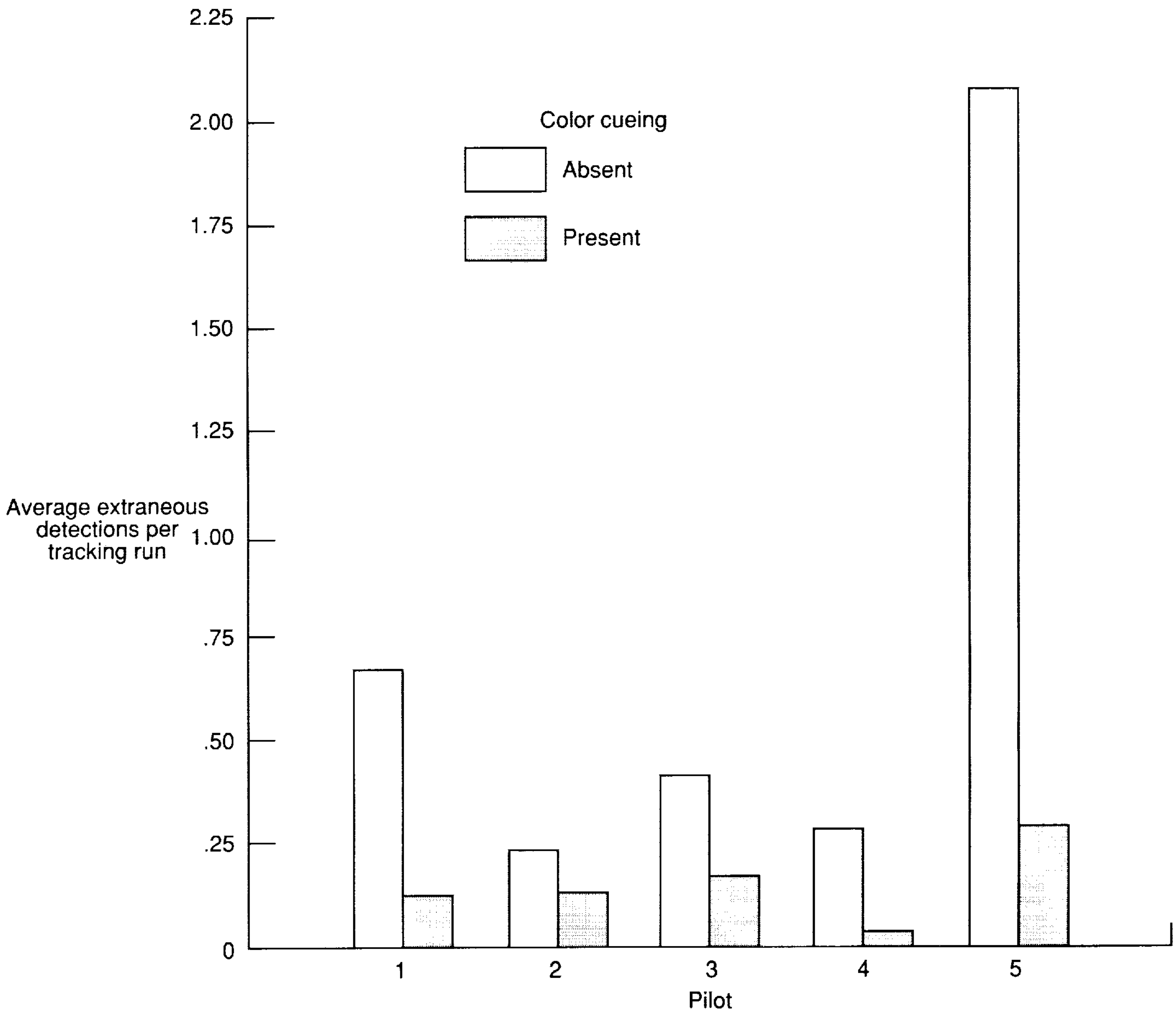



Figure 54. Effect of color cueing in monitoring task display on extraneous detections for monitoring task for each pilot.

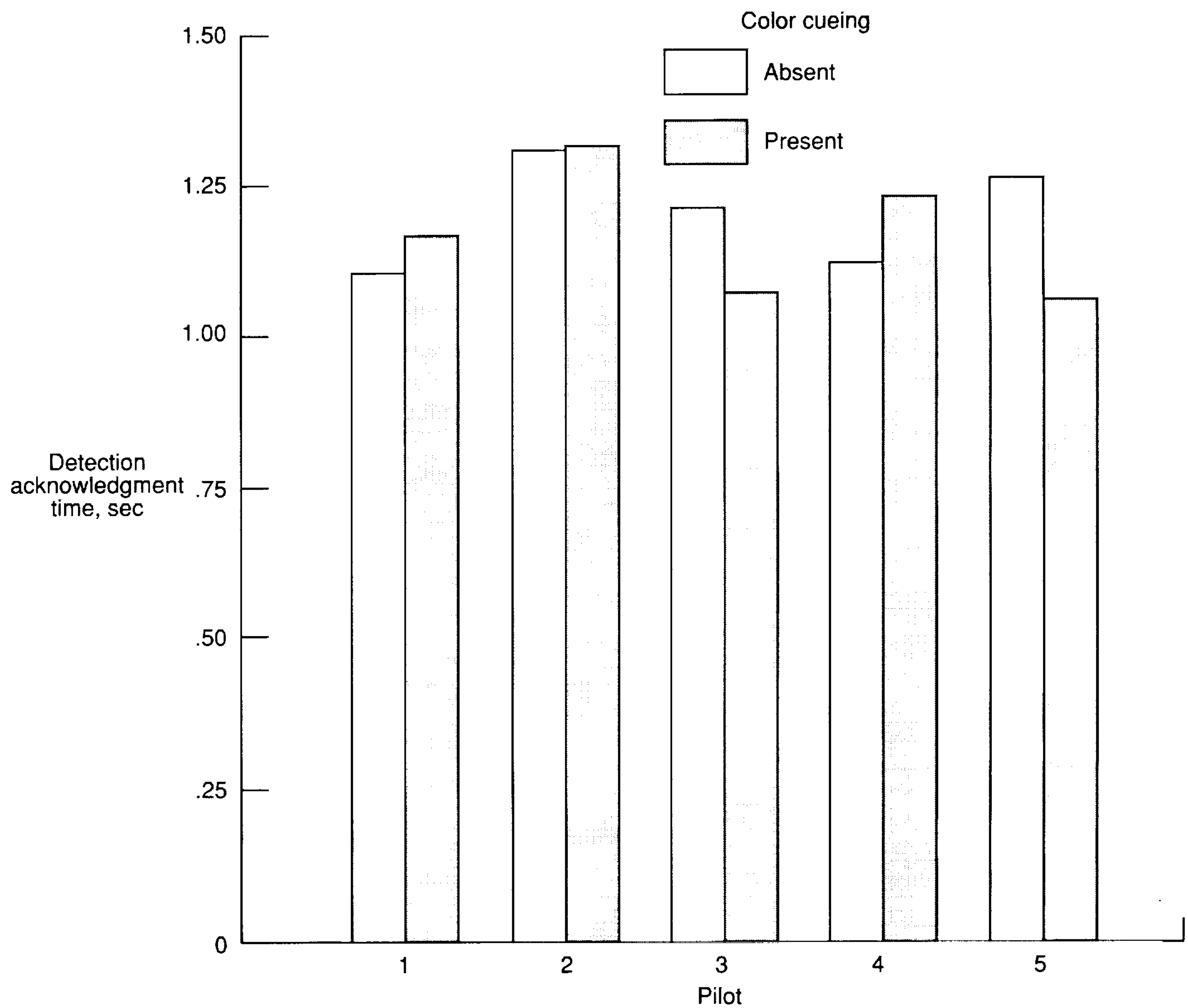



Figure 55. Effect of color cueing in monitoring task display on acknowledgment time for detections in monitoring task for each pilot.

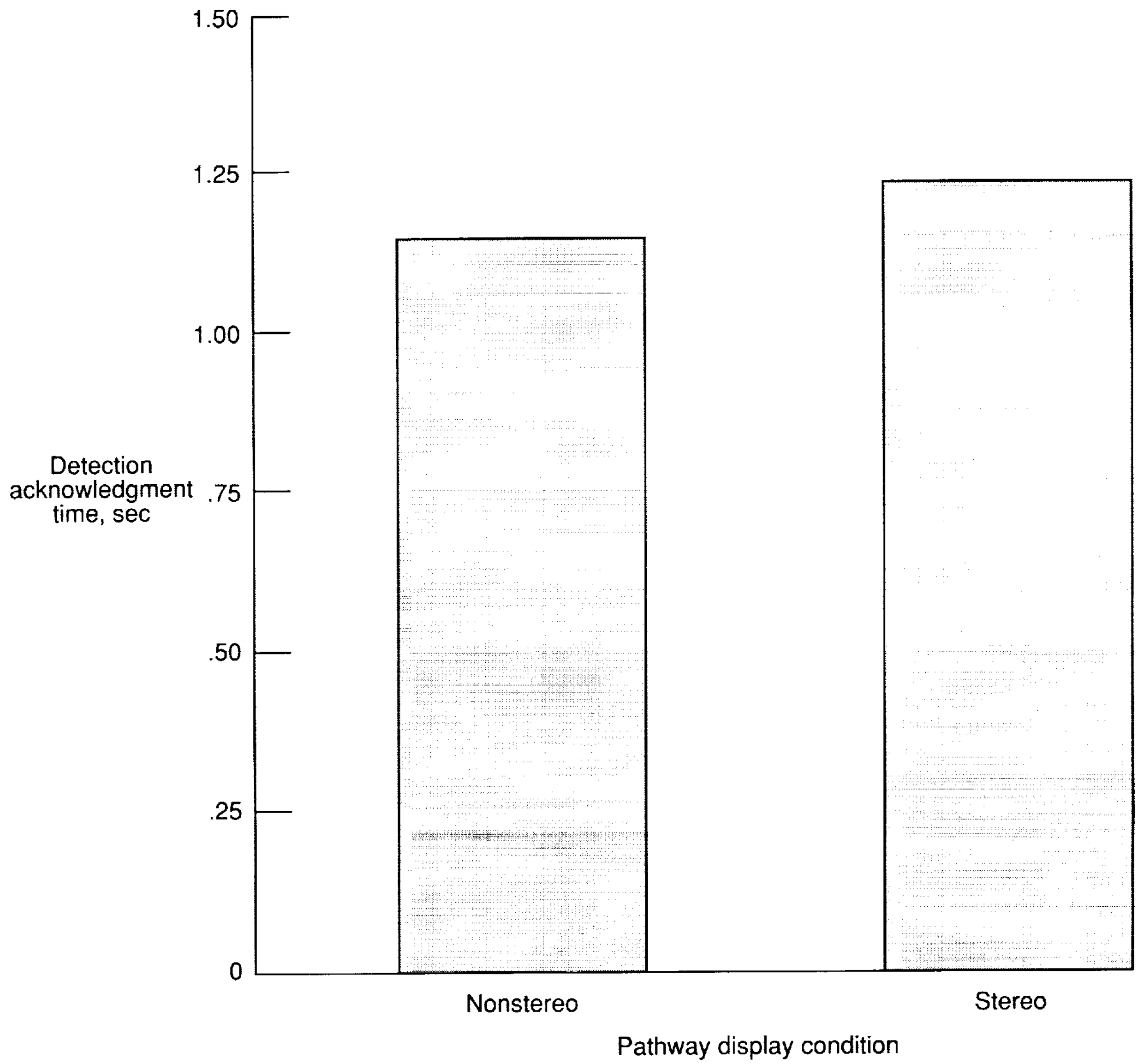



Figure 56. Effect of tracking task pathway display condition on acknowledgment time for detections in monitoring task for all pilots.

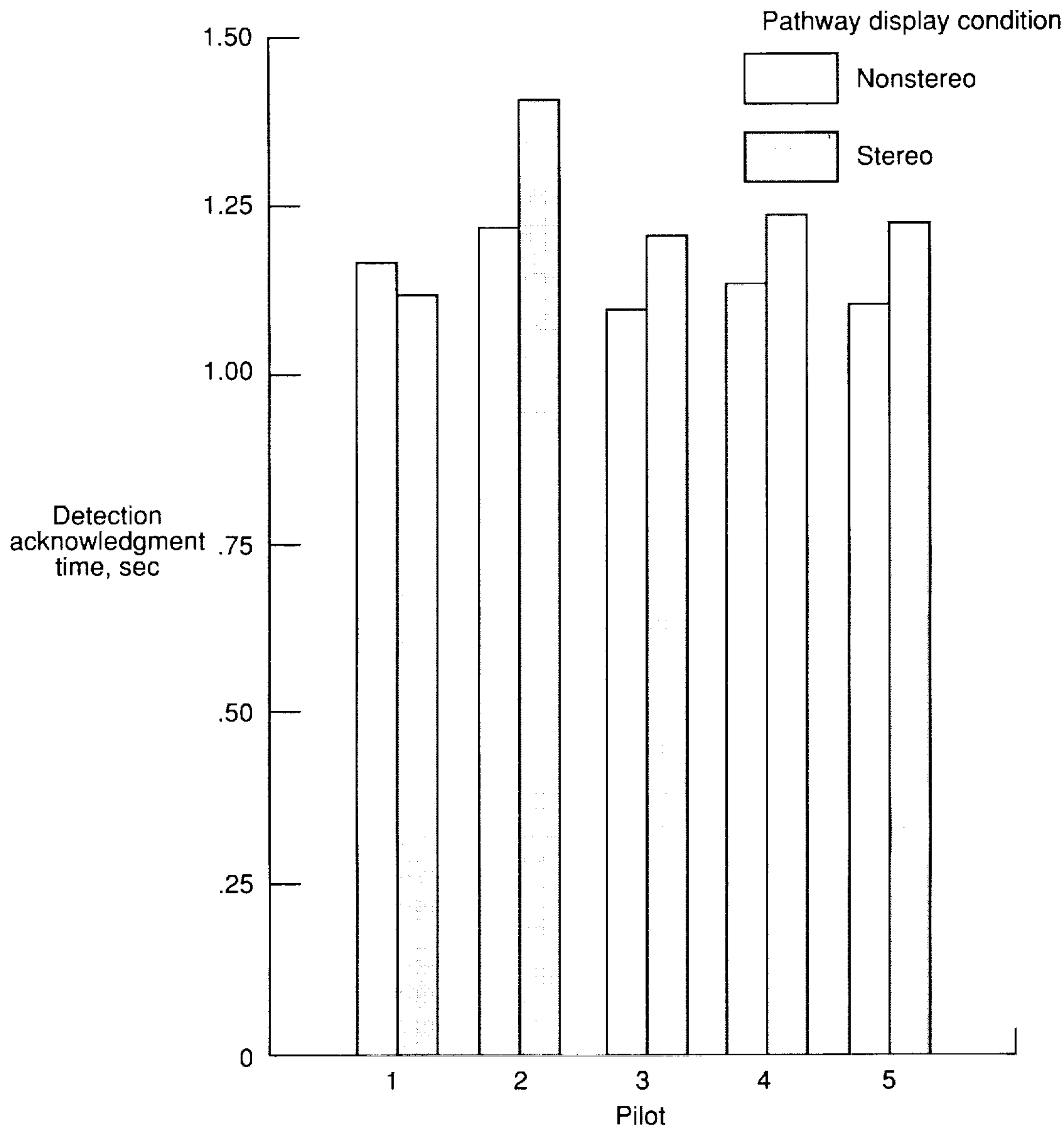



Figure 57. Effect of tracking task pathway display condition on acknowledgment time for detections in monitoring task for each pilot.

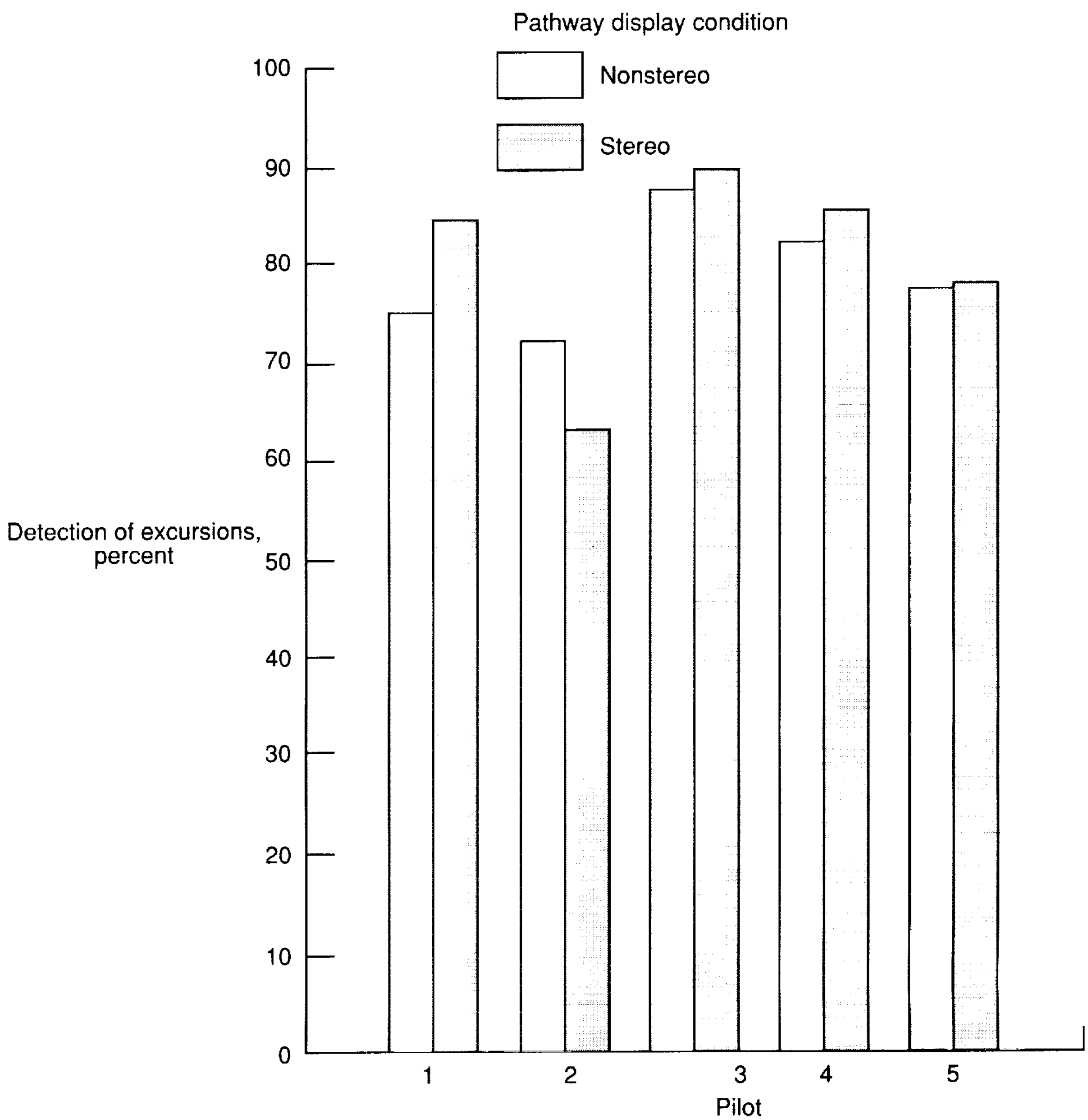



Figure 58. Effect of tracking task pathway display condition on detection percentage for monitoring task for each pilot.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
February 1993

**3. REPORT TYPE AND DATES COVERED**
Technical Paper

**4. TITLE AND SUBTITLE**
Trade-Offs Arising From Mixture of Color Cueing and Monocular, Binoptic, and Stereoscopic Cueing Information for Simulated Rotorcraft Flight

**5. FUNDING NUMBERS**
WU 505-64-13-32
PR 1L161102AH45

**6. AUTHOR(S)**
Russell V. Parrish and Steven P. Williams

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
NASA Langley Research Center
Hampton, VA 23681-0001

Joint Research Program Office
Electronics Integration Directorate
Communications Electronics Command
Langley Research Center
Hampton, VA 23681-0001

**8. PERFORMING ORGANIZATION REPORT NUMBER**
L-17085

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001
and
U.S. Army Communications Electronics Command
Fort Monmouth, NJ 07703-5603

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA TP-3268
CECOM TR-92-B-014

**11. SUPPLEMENTARY NOTES**
Parrish: Langley Research Center, Hampton, VA; Williams: Joint Research Program Office, EID-CECOM, Langley Research Center, Hampton, VA.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified–Unlimited

Subject Category 05

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*
To provide stereopsis, binocular helmet-mounted display (HMD) systems must trade some of the total field of view available from their two monocular fields to obtain a partial overlap region. The visual field then provides a mixture of cues, with monocular regions on both peripheries and a binoptic (the same image in both eyes) region or, if lateral disparity is introduced to produce two images, a stereoscopic region in the overlapped center. This paper reports an in-simulator assessment of the trade-offs arising from the mixture of color cueing and monocular, binoptic, and stereoscopic cueing information in peripheral monitoring displays as utilized in HMD systems. The accompanying effect of stereoscopic cueing in the tracking information in the central region of the display is also assessed. The pilot's task for the study was to fly at a prescribed height above an undulating pathway in the sky while monitoring a dynamic bar chart displayed in the periphery of their field of view. Control of the simulated rotorcraft was limited to the longitudinal and vertical degrees of freedom to ensure the lateral separation of the viewing conditions of the concurrent tasks.

**14. SUBJECT TERMS**
Helmet-mounted display; Stereo; Tracking task; Monitoring task; Stereoscopic cueing; Color cueing

**15. NUMBER OF PAGES**
79

**16. PRICE CODE**
A05

**17. SECURITY CLASSIFICATION OF REPORT**
Unclassified

**18. SECURITY CLASSIFICATION OF THIS PAGE**
Unclassified

**19. SECURITY CLASSIFICATION OF ABSTRACT**

**20. LIMITATION OF ABSTRACT**